VOLUME XXXII NUMBER 6

THE
JOURNAL OF GEOLOGY

August-September 1924

THE TEMPERATURES OF HOT SPRINGS AND THE SOURCES OF THEIR HEAT AND WATER SUPPLY. IV[1]

THE HOT SPRINGS OF ARKANSAS

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The general geologic setting of the Hot Springs of Arkansas, the oldest of our national parks, has been described by a number of authors, but the most comprehensive description of the area appears in the recently published folio by Purdue and Miser.[3] The hot springs are situated in the Ouachita Mountains on the southern border of one of the smaller ranges and on the northern border of an intermontane basin. The rocks are Paleozoic in age and deformed by folding of Appalachian type. The hot water rises through fractured sandstone at the nose of a plunging anticline. Numerous

[1] Continued from *Journal of Geology*, Vol. XXXII, p. 399.

[2] Published by permission of the director of the U.S. Geological Survey, and the director of the National Park Service.

Secretary's note: On account of Mr. Bryan's early departure for field work his paper was presented only by title, and was originally represented among the papers submitted for publication only by a brief abstract. The delays incident to publication have fortunately made it possible, through the kindness of the editors of this *Journal*, to substitute this informative new material for the original abstract.—R. B. S.

[3] A. H. Purdue and H. D. Miser, *U.S. Geol. Survey, Geol. Atlas* (1923), Folio 215.

small dikes cut the folded structures, and near by at Potash Sulphur Springs and at Magnet Cove are small, stocklike intrusions. The igneous rocks are thought to be of Cretaceous age.

The spring openings at Hot Springs are numerous, but all are found within an area of about 20 acres. The total flow has been estimated at 165 gallons a minute and the temperatures range from 35° to 64° C. Analysis of the somewhat random measurements made in the past 120 years gives no trustworthy evidence of a permanent increase or decrease in flow or temperature.

The writer has recently published[1] a description of the geological conditions at the Hot Springs of Arkansas, and to this paper the reader is referred for the details of the geological work done at Hot Springs in 1921. The hypotheses which have been proposed to account for the supply of heat and water are summarized below, but, in the paper already referred to, the history of speculation regarding the origin of the water and heat is reviewed at greater length.

There are three principal hypotheses of origin. According to the one having the greatest number of advocates, the water is entirely meteoric and enters a porous bed in an anticline northwest of the springs, passes under a syncline, and emerges in the next anticline because of hydrostatic pressure. Because the probable depth of the line of travel under the syncline is small and heating of the water by depth alone seems improbable, it is assumed that here the water comes in contact with hot rock, perhaps a cooling plug of igneous origin. However, the lowest part of the anticline in which the water is to gather is lower than the highest of the springs; therefore, there can be no movement due solely to hydrostatic head. Evidence is also brought forward to show that there are other springs of strong flow in the surrounding region of similar mineralization and with temperatures above normal. Therefore, a special mechanism for flow or as a source of heat is invalid, and a general cause, capable of producing all the springs, must be sought. On this account the simple hypothesis that the water is derived from a cooling and crystallizing igneous mass directly under the springs

[1] Kirk Bryan, "The Hot Water Supply of the Hot Springs, Arkansas," *Jour. Geol.*, Vol. XXX (1922), pp. 425–49.

seems unlikely, for it would be necessary to postulate several such masses distributed over an area 50 miles in diameter, and there is no other evidence of igneous activity save the dikes and stocks, previously referred to, which are of Cretaceous age.

It seems more likely that in the Pleistocene uplift of the region deep fissures or faults were formed of which no surface expression has been discovered. These fissures doubtless extend into the deep interior of the earth whence juvenile water rises and, mixed with meteoric water, comes to the surface through shattered rock at the end of the Hot Springs anticline. In its rise this water is purged by various chemical reactions of most of its original dissolved contents and has acquired the moderate mineralization now characteristic.

It is obvious that such a theory rests on general argument, yet the geological setting and the details of the local structure are relatively well known. It also seems unlikely that further study of the structural geology or geologic history will shed much light on the problem. Locally, the rocks have been mapped to an accuracy of 25 feet in the position of contacts, and, except for artificial exposures that may be made in the future, little new information can be gained by the ordinary methods of geologic inquiry. Therefore, further work must be directed toward the collection of physical and chemical data that, it is hoped, will yield useful information on the problems involved, and lead to specific rather than general evidence in favor of one or other of the proposed theories of origin.

On a second visit to Hot Springs in September, 1922, the writer made observations on temperature and flow of certain springs, and discovered fluctuations heretofore unrecognized. These observations, begun for administrative purposes, have been continued to the present date by the National Park Service, through the interest of the administrative officials in Washington and of the superintendents at Hot Springs—Dr. C. H. Waring until April, 1924, and Dr. J. E. Bolten, the present incumbent. Except for the initial five days' observations all readings and measurements have been made, under detailed instructions from the writer, by William F. Walters, whose faithful and careful work is much appreciated.

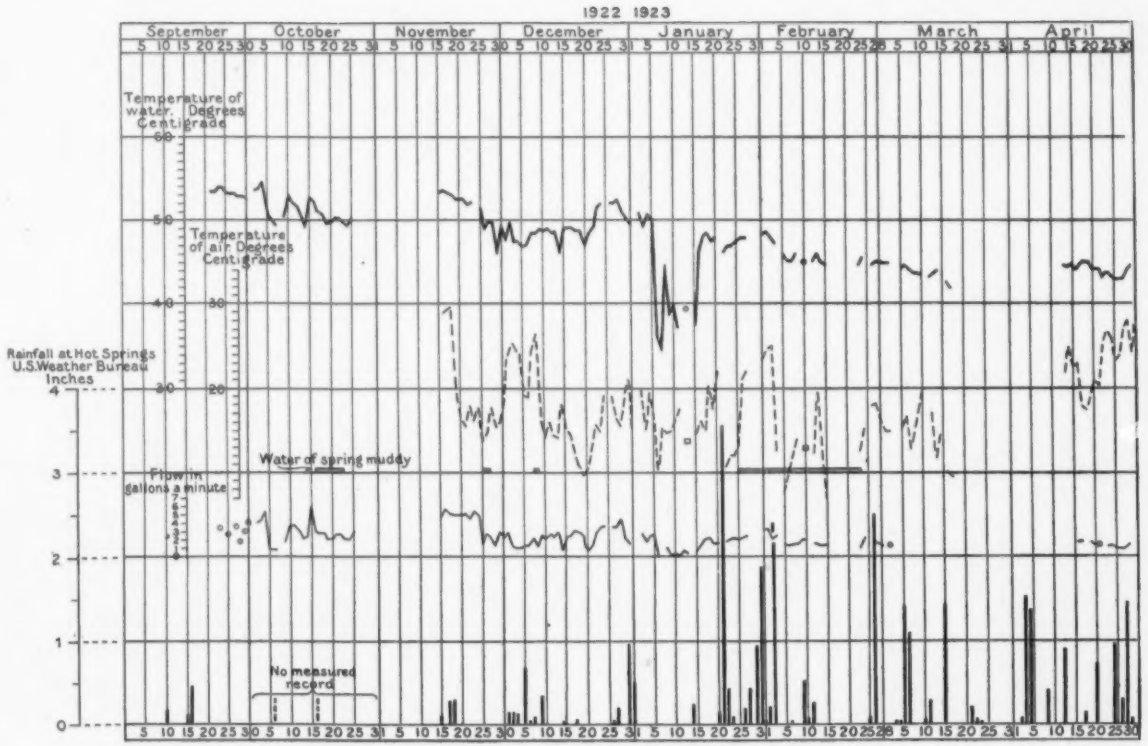
The hot springs have been in use as a bathing resort since prehistoric time, but active interference with natural openings began between 1860 and 1870 when open wooden troughs as a means of conveying hot water to the bathhouses were replaced by pipes. The most extensive changes were made in 1890–92 when the hillside above "Bathhouse Row" was converted into a park by landscape gardening. Since that time a complicated system of spring structures, collecting reservoirs, and pipe systems has been evolved that makes impossible a measurement of the total flow of the springs at any one instant. Existing "measurements" are summations of the flows of individual springs taken at intervals extending over a week or more. Only a few of the springs are sufficiently accessible so that even temperature observations can be made at frequent intervals. Due to these practical difficulties the system of measurements set up in 1922 is incomplete and inadequate for a complete analysis. The results so far obtained are, however, interesting and suggestive, and it is hoped that a continuation of the observations will yield data not only useful in the administration of the national park, but of scientific value.

Measurements of temperature have been made at three springs only. The readings are made with a mercurial thermometer totally immersed in the hottest part of the pools in which the water issues. Several thermometers, all centigrade, have been used. The early ones were graduated to degrees only, and it was necessary for the observer to estimate tenths. The present type read directly in tenths of degrees. The corrections to be applied to the readings are all small, and for some of the instruments can be disregarded. The ordinary time of observation is from eight to nine in the morning, and more than one reading was made on a few days only. Nearly every Sunday is missing, and there are other gaps in the record for various causes. Of the three springs two have rather strong flows and emerge in the basements of bathhouses where they are protected from the extremes of air temperature. The third spring, known as the "Stevens," or "No. 37," emerges on the hillside under a masonry arch and within a masonry curb, from which it overflows through a pipe. The pool of water is 3 feet long by 2 feet wide and 2 feet deep. It is possible to measure the flow of this

spring by turning a valve and allowing the water to flow into a bucket, and this measurement has been made at the same time as the observations on temperature.

Data pertaining to Stevens Spring for the period September 20, 1922, to January 31, 1924, are shown graphically in Figure 1. A preliminary examination indicates that during the period the flow varied from zero to 6 gallons a minute, and the temperature from 34.4° C. to 54.5° C., a range of 20 degrees. From September 20 to December 30, 1922, the temperature exceeded 50° C. frequently, but since that time such high temperatures have not occurred, the maximum being 48.5°C. During the period of high temperatures the largest flows were recorded, and there is a nice correlation of flow and temperature, the highest temperatures being recorded at times of greatest flow. There is evidence, not as complete as one would wish, that artificial draft on sources situated at lower levels caused the lower flows during this period. The lower temperatures at these times were therefore consequent on cooling of the diminished quantity of water passing through the spring opening into the masonry basin. The air temperature at the time of reading the water temperature was recorded from November 16, 1922, to January 31, 1923, but it is obvious from an inspection of the plotted curves in Figure 1 that this temperature is not decisive. It is the accumulated deficiency of temperature through the preceding night that cools the water. From January 6 to January 16 the temperatures of the spring water that were recorded are very low and on several days fall below 40° C. During this period the flow is also very small, and on January 6 the spring was dry. Heavy pumping from a source of hot water at a lower level is also recorded at this time and is the proximate cause of this low flow. The unusually low temperatures are the necessary consequence of the cold weather of winter and the slow rate at which water entered the basin.

After January 30, 1923, the correlation between temperature and flow is not obvious. The flow is small and relatively constant, ranging from 1 to 2 gallons a minute, and there seems to be no tendency toward the large flows and high temperatures of the previous period. However, the air temperature at the time of reading seems to have more importance, and in a number of instances


1922 1923
September
October
November
December
January
February
March
April
Temperature of water. Degrees Centigrade
60
50
40
Temperature of air Degrees Centigrade
30
20
Rainfall at Hot Springs U.S.Weather Bureau Inches
4
3
2
1
0
Flow in gallons a minute
Water of spring muddy
No measured record

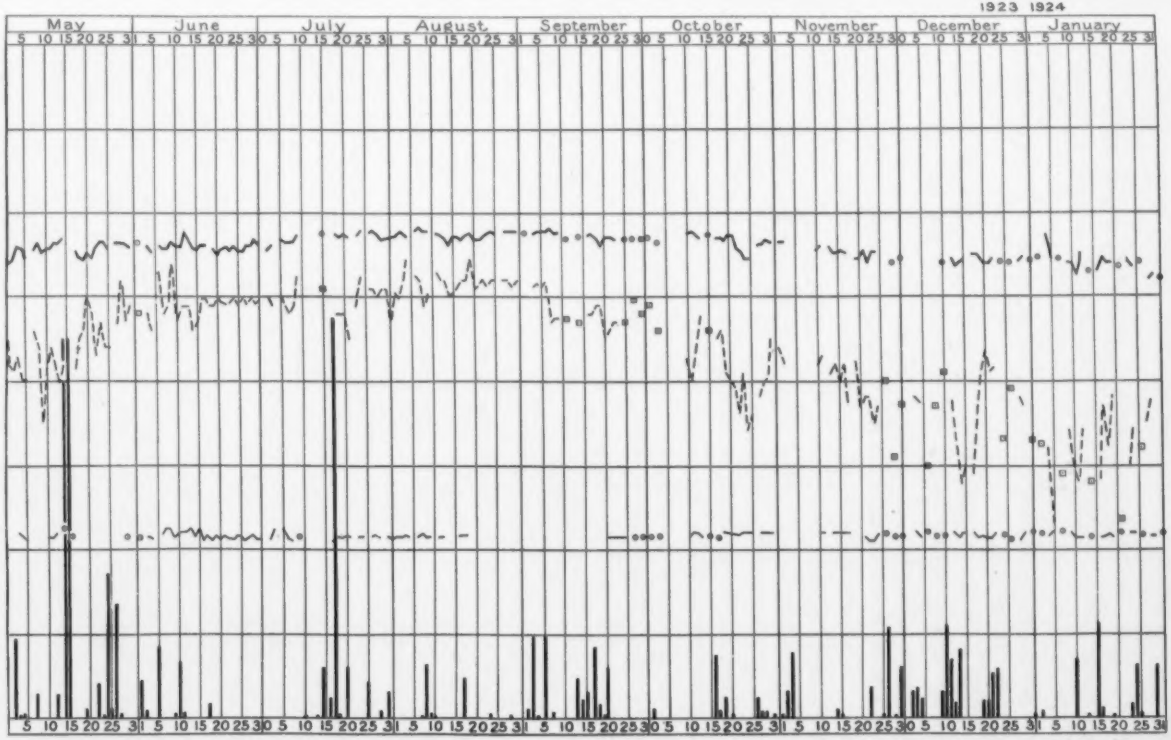


FIG. 1.—Observations at Stevens Spring, September 20, 1922, to January 31, 1924. Readings of temperature of water in heavy line; of temperature of air in dashed line; of flow in medium line.

there is some similarity between the curves of air and water temperature, as plotted in Figure 1. This tendency is more noticeable in the winter months. It is probable that this correlation between temperatures of air and water is a consequence to be expected at periods of low flow.

The influence of rainfall on the flow and temperature of the spring is not wholly clear. Table I summarizes the rainfall of the years 1921–23.

The observations recorded in Figure 1 were started in September, 1922, in a notable period of drought that began in May, 1921, and continued to January 20, 1923. During this time the accumulated deficiency exceeded 17 inches, and only one month, March, 1922, had a notable excess of moisture. It is possible that the high water-temperatures observed from September 20 to December 30, 1922, may have been due to the drought and consequent lack of contamination of the hot water by local seepage. Certainly the small rains of October, November, and December tended to make the water of the springs muddy or turbid, and the rainy period from January 18 to February 11, 1923, brought on a long spell of muddy water (see Fig. 1). However, there is no evidence that rains increased the flow of water, nor is muddy water recorded during the remainder of the wet year of 1923 when the excess of rainfall was 13.21 inches. It seems, therefore, that the existing data are inadequate to show the relation, if any exists, between rainfall and the flow and temperature of the spring.

The general course of the temperature curve, disregarding the fluctuations from day to day, shows a seasonal swing. Higher temperatures from July to the middle of November and lower temperatures during the rest of the year are recorded. Doubtless this swing is due to the change from summer to winter. The lower air temperatures of winter affect the water in the spring basin and doubtless also the upper 20 feet or so of the rock conduit from which the spring issues. However, the use of water and therefore the draft on sources that may affect the flow of Spring No. 37 varies through the year. This fluctuation can be indirectly measured in the income of bathhouses for which statistics have been gathered for many years. As shown in Figure 2, the months January to

TABLE I

MONTHLY AND ANNUAL RAINFALL, IN INCHES, AT HOT SPRINGS, ARKANSAS, WITH DEPARTURES FROM THE NORMAL FOR THE YEARS 1921–23

(From published data of the U.S. Weather Bureau)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1921	1.61	4.83	7.21	9.07	0	3.40	1.85	4.40	3.29	0.49	5.89	3.62	45.66
Departures from normal	−3.49	+0.96	+2.13	+3.01	−6.01	−1.34	−2.69	+0.57	−0.29	−2.21	+1.42	−0.68	− 8.62
1922	1.90	4.21	9.58	4.80	7.41	3.40	4.44	2.22	0.72	3.22*	0.64†	3.25	45.79§
Departures from normal	−3.20	+0.34	+4.50	−1.26	+1.40	−1.34	−0.10	−1.61	−2.86	−0.87*	−3.83‡	−1.05	− 8.49§
1923	9.55	5.10	4.64	7.81	14.26	2.41	7.10	1.30	4.83	1.56	3.37	5.56	67.49
Departures from normal	+4.45	+1.23	−0.44	+1.75	+8.25	−2.33	+2.56	−2.53	+1.25	−1.14	−1.10	+1.26	+13.21
Means	5.10	3.87	5.08	6.06	6.01	4.74	4.54	3.83	3.58	2.70	4.47	4.30	54.28

* Record at Mount Ida, Arkansas.

† Incomplete record.

‡ Too large by small amount.

§ Approximate value due to substitutions noted in *, †, and ‡.

April, inclusive, are the period of large business and heavy draft. September to November, inclusive, are the months of minimum income and therefore of draft. This seasonal fluctuation resembles the seasonal swing in temperatures previously described and may be a factor in its production. If the record can be maintained for several additional seasons, analysis of this factor and its relation to the seasonal change in the climatic elements can be made more definite.

The two strong springs have very small fluctuations in temperature. One of them has a total range of half a degree centigrade, the other of 1.4°. Unfortunately, it is impossible, except at considerable expense, to measure the flows of these springs. The record of

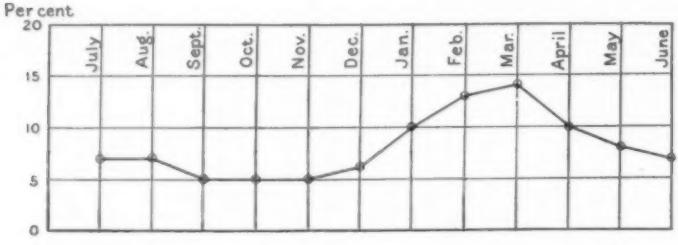


FIG. 2.—Diagram showing the variation by months in the use of hot water expressed in percentage of the mean income of bathhouses for the years 1915–20.

fluctuations in temperature has not yet been thoroughly studied, but there is no doubt that the recorded variations in temperature are real and not due to errors, and that a seasonal swing similar to that shown in the record of the Stevens Spring seems to hold for these larger springs.

General conclusions can hardly be expected at this stage of the observations briefly reviewed above, and must await a longer period of record and a more complete analysis. Irrespective of the ultimate origin of the water, its passage through the surface rocks within the zone of seasonal change in temperature and its issuance into a spring basin will produce seasonal changes such as have been recorded. The high temperatures and strong flow of the Stevens Spring in the fall and early winter of 1922 were not repeated in the

same period of 1923 and may, in this instance, be due to differences in climatic factors, specifically the abnormally dry seasons of 1921 and 1922, or may be due wholly to artificial control. The element of artificial control is, until much longer and more complete records are available, almost impossible to eliminate in the study of the fluctuations in flow of these springs.

One of the most useful things brought out by the records is the mere fact of fluctuation and its range, amounting to 20° C., in a spring of small flow. Random measurements of temperature in such springs seem, in the light of this experience, to have small value. Even springs of relatively large flow protected from extremes of air temperature have detectable variations in temperature.

HOT SPRINGS AND FUMAROLES OF "THE GEYSERS" REGION, CALIFORNIA

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(Notes by the Secretary)

The speaker visited the region in 1922, with the permission of the owner of the property, and made measurements of temperatures and other observations on the fumaroles and springs, but the detailed data are not yet available for publication.

These hot springs and fumaroles—they include no true geysers—are in Sonoma County, California, about 70 miles northwest of San Francisco. They are in a general hot-spring region which includes the neighboring counties of Lake and Napa, at the western base of the Coast Range. A description of "The Geysers" has been published by Waring,[1] with twelve analyses of the waters. The temperatures of the springs whose waters were analyzed were from 21° to 100° C. The temperature in 1909 of the best-known fumarole vent, known as Steamboat Geyser, is given as 205° F., but much higher temperatures are known to exist in the region.

[1] G. A. Waring, *Springs of California, U.S. Geol. Survey Water-Supply Paper 338*, 410 pp., 13 pls., 1915. ("The Geysers," pp. 83–88, Plate X.) This publication contains the most complete available description of the hot springs of California.

According to recent news reports,[1] steam from one of these fumarole vents is being utilized for the generation of power—the first application in the United States of methods now in active use in Northern Italy.

NOTES ON THE SOLFATARA OF SOUSAKI (GREECE), A RECENT ERUPTION AT METHANA (GREECE), AND RECENT MACCALUBE AT VULCANO

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Sousaki

There is an interesting and little-known solfatara at Sousaki, near Kalamaki, about 5 miles east of the Isthmus of Corinth. This has been described briefly by Reiss and Stübel[2] and by Philippson,[3] and was visited by the speaker in March, 1893. The solfatara consists of a narrow valley in late Tertiary (Neogene) marls and conglomerates, near an intrusion of serpentine and gabbro. Carbon dioxide is given off abundantly, in one cave the gas coming up to one's knees, and there was a copious emission of hydrogen sulphide and sulphur dioxide at the time of the visit in 1893. The locality is worthy of further study. Near by is an extensive flow of dacite, with many phenocrysts of bluish quartz,[4] which is covered by Pliocene marls and may be due to a submarine eruption.

The solfatara of Sousaki is of interest because it is apparently at the northern extremity of the line of Aegean volcanoes, which includes Methana, Aegina, Milos, Santorini, and Nisyros. Of these, Nisyros was in eruption in 1873 and 1887, but when visited by Martelli[5] in 1912 was in a solfataric state. Santorini was last

[1] *Popular Mechanics Magazine*, Vol. XXXIX (May, 1923), pp. 705–6.

[2] Reiss and Stübel, *Ausflug nach Aegina und Methana* (Heidelberg, 1867), p. 51.

[3] A. Philippson, *Der Peloponnes* (Berlin, 1892), p. 21.

[4] H. S. Washington, *Jour. Geol.*, Vol. II (1894), p. 806; *ibid.*, Vol. III (1895), p. 44.

[5] A. Martelli, "Il gruppo eruttivo di Nisiro," *Mem. Soc. ital. Sci. dei Quaranta*. Vol. XX (1917), pp. 79–165, with geological map.

in eruption from February, 1866, to October, 1870,[1] and only a little steam and hot vapors were coming from the recent crater of Giorgio Kaimeni when I visited it in 1893.

METHANA

Strabo, Pausanias, and Ovid speak of an eruption on the peninsula of Methana, which took place about the year 250 B.C. The site was at a spot on the north shore, called Kaimeni (meaning *the Burnt*, not the same as the crater referred to in the preceding) where there is a small volcanic cone with a crater and a fairly fresh looking lava stream that flowed into the sea. When I saw it in 1893 there was no sign of activity.[2]

According to the Italian newspapers a volcano on Methana (possibly at Kaimeni) was in eruption in August, 1922, shortly before I left Italy. The newspaper reports were confirmed by Mrs. G. P. Stevens, wife of the director of the American Academy at Rome, whose sister was staying on Aegina and who wrote that they had been watching for some days the smoke from the recent volcano on Methana about 10 miles away. In the paper cited previously the suggestion was made that possibly Methana is not quite extinct, and this reawakening after a period of about 2,170 years, the longest-known period of repose between outbreaks of any volcano, is of some special interest. It would be of considerable importance to study the lavas of this latest eruption, and I am making an effort, through the medium of Professor C. D. Buck, who is to be director of the American School at Athens, to obtain specimens of the lavas and reliable accounts of the eruption.

At the same time, it would be of interest to get information on the activity at Sousaki, with more detailed data than have yet been available, such as temperatures and the amounts of gases and water. If some general underlying change is reawakening the volcano at Methana, it might conceivably be indicated more clearly in this limiting solfatara of the chain than in the more complex and obscure phenomena of the volcanoes themselves.

[1] F. Fouque, *Santorin et ses eruptions* (Paris, 1879).

[2] H. S. Washington, *Jour. Geol.*, Vol. XVI (1894), p. 16.

VULCANO

The recently formed, small mud volcanoes or *maccalube* at Vulcano, Aeolian Islands, were visited in May, 1922, on the excursion taken by some of the volcanologists after the meeting at Rome of the International Union of Geodesy and Geophysics. Part of the low flat land at the Porto di Levante, on the neck between the Fossa di Vulcano and Vulcanello, was covered with many small maccalube, which started a few years ago and destroyed the garden and orchard near the large house of the proprietor of the volcano. The maccalube consist of rounded pits, a few feet in diameter, filled with boiling gray mud of a creamy consistency, giving off abundant carbon dioxide but no sulphur vapors. The temperature of these mud pits was found to be very constantly 95° C. Clear water, highly charged with carbon dioxide, issues abundantly through the sand of the beach near by, north of Il Faraglione, and these flows had a temperature of 100° C. Carbon dioxide was issuing from the adjoining sea bottom, and the water was variably warm to hot. Some similar outflows of hot water, less charged with carbon dioxide, occur on the seashore on the south side of the cove at Il Bianco; here temperatures up to 82° were noted.

THE HOT SPRINGS OF ICELAND

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Iceland has much of interest for the student of volcanology. The island is volcanic in origin and consists essentially of basaltic lavas with a few rhyolites interspersed; these lavas range in age from Tertiary to recent and are part of the great plateau basalt area that extends from Ireland, through the Inner Hebrides, the Faroe Islands, into Iceland and Greenland. In Iceland, post-glacial basalts and tuffs cover nearly half the entire area and show how extensive volcanic activity has been, even in recent times. Because of the high latitude of the island, timber is absent and everywhere the rock exposures are excellent and favorable for geological studies.

The volcanic phenomena have long attracted attention and many scientists and explorers interested in geology have visited the island and published the results of their investigations. In 1844 Bunsen and Des Cloizeaux journeyed to Iceland and, while at Geysir, developed their theory of geyser action; it was as a result also of his studies in Iceland that Bunsen formulated his petrogenetic theory of igneous rock formation through mixtures of basaltic and rhyolitic original magmas.

In recent years the most important contributions to the geology of Iceland have been made by T. Thoroddsen, who has spent his life in geologic reconnaissance work in all parts of the island. The most thorough studies on the hot springs of Iceland were made by T. Thorkelsson in 1904 and 1906. He examined the hot springs in southwestern, central, and northeastern Iceland near Myvatn. He made careful temperature measurements at the springs, also chemical analyses of the gases and waters, and estimates of their radioactivity. His excellent work is, however, only the beginning of what must be done if the many problems connected with this phase of volcanology are to be solved.

In 1909 I spent nearly a month crossing and recrossing the island and visited many hot springs and geysers. The time, however, was too limited for detailed work, and small collections only could be made of the sinter deposits and surrounding rocks. Throughout the trip we were impressed with the wealth of material available in Iceland for the study of nearly all phases of volcanic activity. The field relations are so clearly shown that it is a simple matter, in most cases, to decipher the geologic history. There are hundreds of postglacial volcanoes and lava flows, exhibiting the many surface phenomena characteristic of basaltic lavas; many fissures still exist through which great masses of lava welled up and flooded the surrounding country for hundreds of square miles, thus producing the familiar plateau type of basalt. The somber cliffs which fringe the coasts of Iceland, the fault escarpments which mark the edges of great fault blocks, and the walls of the deeply incised valleys and canyons, afford opportunity for the detailed study of the succession of lava flows. There are thousands of hot springs and geysers. The entire island from southwest to northeast is

evidently underlain with still hot rock masses near the surface which do not cool off rapidly and which serve as sources of heat for circulating waters and also as sources of magmatic waters and gases.

To obtain satisfactory results in a region of this character it is necessary that detailed studies of the principal springs be carried on over a period of years; in other words, the period of reconnaissance work on the hot springs of Iceland has passed and we are now entering upon the period where quantitative, detailed work is essential to progress in this phase of the science of volcanology.

NOTES ON THE DISCUSSION OF THE PAPERS PRESENTED IN THE SYMPOSIUM ON HOT SPRINGS

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Geophysical Laboratory, Carnegie Institution of Washington

Available supply of juvenile water.—One of the questions raised in connection with the theory of juvenile water, used by Day and Allen in the first paper of the series, has to do with the amount of water available for the maintenance of springs through long periods of time. A simple calculation serves to show the order of magnitude and the possible limitations. For the purposes of calculation suppose:

an igneous magma 1 km. in vertical thickness and of indefinite horizontal extent;
density of the magma = 2.5;
proportion of water in the magma = 5 per cent by weight;
time of cooling = 1,000,000 years;
water given off completely at a uniform rate during the cooling.

Under the foregoing conditions there could exist on any area of the earth's surface 10 km. square, directly overlying the magma, a fumarole with a flow of steam equivalent to 23.8 liters of water per minute. If this were to be mixed with nine parts of meteoric water in the manner described by Day and Allen, it would yield a hot spring of 238 liters per minute, or roughly, half the present output of the Hot Springs of Arkansas. This would continue uninterruptedly for a million years.

The proportionate increase in flow corresponding to shortening the time, increasing the percentage of water, or extending the area or thickness of magma drawn upon, will be obvious.

This same calculation would apply to another source of hot-spring water which has perhaps not received the attention it deserves in the foregoing symposium, namely, water driven out of hydrated minerals and out of sedimentary rocks by slowly rising geotherms.

Forced flow as a source of heat in low-temperature springs.—In connection with the paper by Adams the question was raised whether a part of the heat in such low-temperature springs as those in the Appalachians might not be due to forced flow. The transfer of a mass of water from a high level to a low level involves the loss by the water of a certain amount of potential energy. This must either be distributed along the route or appear in the water itself at its final location, either as kinetic energy or as heat. Under most circumstances of flow the heating is not appreciable, but if there is a sudden change from a high pressure to a low pressure at some point along the route there may be a localization of energy at that point in the form of heat, and an appreciable rise in temperature. This question is worth consideration by those familiar with the facts of the flow of underground water.

Age of hot springs.—The question of the known age of hot springs was brought up, following Washington's paper. The hot springs of France were mentioned as among the oldest of historic record. The occurrence of Roman masonry in some of these springs, as well as the character of the minerals deposited thereon, shows that the springs were flowing over 2,000 years ago under conditions not very different from those of today. Wright pointed out that the hot springs of Iceland are associated with postglacial flows, and their age is therefore of the order of magnitude of 10,000 to 50,000 years. Some of the Yellowstone Park springs are known to be preglacial, and are probably over 20,000 years old.

Convection and circulation.—Van Orstrand's opinion that convection plays no part in the transmission of heat from depth led to mention of Thorkelsson's hypothesis concerning the geysers and hot springs of Iceland, that the heat is brought up by a circulating water system whose water does not appear at the surface at all.

It is supposed to receive heat from hot rocks at great depths and to deliver this heat to the ground water which appears in the springs and geysers.

If juvenile water is being contributed from a magma, we must suppose that it is added to Thorkelsson's circulatory system at the bottom while an equal quantity is withdrawn at the top and added to the ground water.

As to the likelihood of convection, a static liquid is almost inconceivable to a physicist, especially a liquid which expands on heating and in which the lower layers are hotter than the upper. Yet Van Orstrand finds no evidence of a general circulation in water-filled wells. It seems necessary to believe that the circulation in such wells is of the character described by Mendenhall and Mason[1] in 1921, consisting of a series of short "cells" each containing within itself a closed circuit.

A circulation of this kind is hardly to be expected, however, in narrow fractures and fissures. Rather must we expect that in certain parts of a fractured rock mass the movement will be prevailingly upward, in other parts downward.

Deposition of minerals.—Morey's paper brought out various questions on ore deposits and the deposition of vein minerals, but limitations of time made it impossible to do more than touch upon this complex subject. It was suggested that the constancy of composition and association of ore minerals found at depth is evidence that temperature is the principal controlling factor, rather than composition of the solutions. In reply it was pointed out that in a heterogeneous system the composition is a function of the temperature, so that it is hardly profitable to try to explain a mineral sequence by considering either composition alone or temperature alone; the two necessarily go together.

It was also brought out that the loss of heat from the escaping solution as it rises through the earth, tending toward a lowering of the temperature, causes changes of equilibrium in a direction to evolve heat and so maintain the temperature. The process of cooling is thereby retarded, though never checked.

Forced flow of steam.—The production of heat by the flow of steam, already referred to by Adams, was again brought up. It was

[1] *Proc. National Acad. Sciences*, Vol. IX (1923), pp. 199–202.

shown that the amount of heat available for raising the temperature in this manner depends upon the equation of state of steam, which is not known for steam at high temperatures. If it were an ideal gas, no heat would be available. If we assume that it follows some other equation of state, such as Van der Waals', then expansion from a sufficiently high initial pressure would raise the temperature.

It was pointed out that the *localization* of high temperatures by such means is the important point. It may lead to such effects as the "gas fluxing" or "blowpiping" postulated in general terms by Daly, resulting in such well-known geological phenomena as volcanic stocks, necks, and pipes.

Literature on hot springs in the United States.—In connection with the paper by Meinzer, it was stated that Miss N. E. Dowell, at the U.S. Geological Survey, had begun a compilation of the available data on the hot springs of the United States. There has been no general publication on this subject since the paper by Gilbert.[1] That paper listed the known hot-spring localities to the total of 136, distributed as follows:

Appalachian region (chiefly Virginia)	15
Arkansas and Texas	2
Montana and Idaho	10
Wyoming	8
Colorado	15
Utah	20
Arizona and New Mexico	15
Nevada	27
California and Oregon	24

The general distribution shown in Gilbert's table and map will not be changed much by later data, but a great deal of information on composition, temperature, flow, etc., has been accumulated in the ensuing forty-eight years.

The most complete report on the hot springs of California is contained in Waring's bulletin.[2] Those of Colorado are described

[1] G. K. Gilbert, "Localities of Thermal Springs in the United States," *Engineer Dept., U.S.A., Rep. Geographical and Geological Explorations and Surveys West of One Hundredth Meridian* (*Wheeler Survey*), Vol. III (1875), pp. 145–55, Plate III.

[2] G. A. Waring, *Springs of California, U.S. Geol. Survey Water-Supply Paper 338*. 410 pp., 13 pls., 1915.

in a recent bulletin of the geological survey of that state.[1] Data on most of the other hot-spring areas of the United States will be found in various publications referred to in the papers of this symposium, although no attempt has been made to complete the references. A large amount of information on American hot springs is doubtless contained in geological publications whose title gives no indication that such information is included, and a systematic search such as that proposed by Miss Dowell will be extremely useful in making such information quickly accessible.

GENERAL SUMMARY OF THE SYMPOSIUM ON HOT SPRINGS

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The foregoing papers contain descriptions of hot-spring activity covering a wide range of temperatures, all the way from those found in warm springs in the mountains of Virginia, some of which are only slightly above the annual mean temperature, up through boiling springs and mud pots, such as are found in our Western volcanic regions, to fumarole temperatures of about 650° C., the highest temperature found in the Valley of Ten Thousand Smokes, Alaska. These various kinds of activity are classifiable in a number of different ways according to the purposes of the classification, but when regarded, as they are here, simply as outpourings of heat energy at the earth's surface, through the intermediary of liquid or gaseous water, they may be considered as members of a continuous series.

Regarding the sources of the heat, it is clearly shown in the paper by Day and Allen that chemical reactions, such as can be inferred from the composition of the spring waters, are not adequate to account for more than a very small proportion of the heat. Similarly, radioactivity, so far as it can be inferred from the radioactivity of the waters, is also insufficient to supply much heat. The radioactivity shows no parallelism with the temperatures of

[1] R. D. George, and others. *Mineral Waters of Colorado, Colorado Geol. Survey Bull. 11.* 474 pp., 2 pls., 1920.

the springs, as has been shown by Thorkelsson, in Iceland, by Schlundt and Moore, in the Yellowstone, and by Hemmeter and Zueblin, in Virginia.

Adams shows that the forced flow of a fluid from a high pressure to a low pressure through a porous plug may develop considerable heat. For liquids there may result a temperature increase of as much as 20° for 1,000 atmospheres' fall. In fact, the passage of any material from a region of high pressure to one of low pressure will usually produce a rise in temperature. It was brought out in the discussion that this process will always be operative to some extent where water is flowing, and it may conceivably account for part of the rise in temperature of such springs as those in Virginia, North Carolina, Georgia, and Haiti. Whether or not it is quantitatively important in these cases remains to be shown.

In the discussion of Morey's paper it was brought out that similar heat effects can be obtained by the forced flow of steam. These processes of flow may also be a source of heat in rock magmas. Physical sources of heat of this character have not been considered heretofore, and we lack the geological observations and discussions which would indicate to what extent forced flow is a factor in natural processes.

There is general agreement in the papers and in the discussion, however, that the source of heat in most of the higher-temperature springs and fumaroles is in subcrustal rock magmas, leaving open the question as to how the magmatic heat may have become localized. The point is brought out in several of the papers that there is no direct connection between extrusive rocks and hot springs; both are the results of a common deep-seated cause.

The principal contribution to the problem of the depth from which the heat is being brought is in the paper by Van Orstrand. From his study of geothermal gradients he concludes that the Yellowstone Park waters must bring their heat from depths between 3,400 and 8,000 feet.

Agreement as to the sources of the water supply is not so general as it is on the problem of the source of heat. In the Yellowstone, as described by Van Orstrand, it seems that the greater proportion of the water must be meteoric, that is, from rain and snow. The

same is probably true in Iceland where there is a large supply from snow fields and glaciers. Allen believes that the probability is strong that over half of the water in the springs of Mount Lassen must be from such sources, and Day showed that the water of the hot springs of "The Geysers" region of California, which he described, is also largely meteoric.

Until about twenty years ago it was generally assumed that all the water of thermal springs and geysers is meteoric water. Suess then emphatically drew attention to the likelihood that at least a part of the water comes direct from the magma which is furnishing the heat—the so-called "juvenile" or "telluric" water. Geological and chemical evidence accumulating since that time makes it almost necessary to believe that this is the case, the only question being as to the proportion of juvenile to meteoric water.

It was shown in the discussion that the amount of water which may be dissolved in a batholithic magma, of the chemical character described by Morey, may be sufficient to supply small hot springs for hundreds of thousands of years without any addition of surface water, and Morey also showed that the conditions of crystallization of such a magma may yield water vapor under considerable pressure. It seems very reasonable to suppose that an easily measurable proportion of the water in such places as the maccalube of Vulcano, described by Washington, and the high-temperature fumaroles of Katmai, described by Zies, is original magmatic water.

This seems almost a necessary conclusion on purely geologic grounds for some of the hot springs of southern Idaho, described by Meinzer. It is shown very clearly in the paper by Meinzer that there is no artesian source of water for many of the springs. It is also shown that on the whole the hotter springs are the smaller, indicating that dilution with ground water from moderate depths is responsible at the same time for low temperature and large volume. These springs come through Paleozoic rocks, Cretaceous granite, etc., and have no direct relation to the Snake River basalts, which are now quite cold.

It is evident that our information about the sources of heat and of water supply in hot springs is more qualitative than quanti-

tative. We shall be able to report considerable progress when we can answer the following questions about some particular hot spring: (1) What proportion of the heat is being produced by flow and what proportion is being brought from the earth's interior (a) by conduction, and (b) by convection? (2) What proportion of the water which we see at the surface has recently been in the form of rain or snow, and what proportion has come direct from some igneous magma?

If there are magmas now crystallizing a few thousand feet beneath the surface in such areas as the hot-spring regions of the West, and if the only outward sign of this process is a hot spring, then it seems a reasonable possibility that some information about the magma may be obtainable by studying the hot spring. For this purpose, however, isolated observations at irregular intervals will not be sufficient. A study of the fluctuations of temperature and water supply, as related to meteorological variables throughout the year, would be one way of beginning such an investigation, and other lines of inquiry would probably be suggested by the results.

TERTIARY PLANATION IN IDAHO[1]

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ABSTRACT

Field work by members of the U.S. Geological Survey and others has led to the recognition of an ancient erosion surface or peneplain in parts of Idaho, Montana, and Wyoming. Differences of opinion have arisen regarding the age and character of this peneplain. The problem is regional in character, necessitating more extended field work before a final solution may be reached.

The paper gives a discussion of the problem in the light of studies by the author in southeastern Idaho. It is concluded that the idea of post-middle Miocene planation across earlier Tertiary and older rocks, as advocated for Idaho by Blackwelder and Rich, is not proved by the available evidence. There seems a probability that the erosional history of western and northern Idaho and of western Montana was somewhat different from that of southeastern Idaho or of western Wyoming. For southeastern Idaho the evidence seems to favor pre-middle Miocene planation succeeded by: (1) middle Miocene deformation; (2) late Miocene and perhaps early Pliocene erosion; (3) Pliocene deformation, erosion, and deposition; and (4) early Pleistocene deformation or rejuvenation and subsequent erosion.

INTRODUCTION

The essay here presented is a by-product of the Geological Survey's exploration of the western phosphate field. Although the work was undertaken primarily for the purpose of classifying the public lands, during its execution other problems forced themselves upon the attention of the field geologists, inviting solution. Some of these problems are regional in character, necessitating more extended field work before a final solution may be reached and of this class is the problem of Tertiary planation in Idaho.

It has seemed worth while in this paper to state this problem and to indicate the bearing which the writer's studies in southeastern Idaho have upon it.

SUMMARY OF LITERATURE

In 1912 Umpleby, combining the work of earlier writers with his own observations, described a peneplain in the Salmon River Mountains of Idaho, which he thought was applicable to much of

[1] Published by permission of the director, U.S. Geological Survey. Read by title before the Association of American Geographers at Cincinnati, December 29, 1923.

[2] J. B. Umpleby, "An Old Erosion Surface in Idaho; Its Age and Value as a Datum Plane," *Jour. Geol.*, Vol. XX (1912), pp. 139–47.

the state, and which he referred to the Eocene. Blackwelder[1] criticized Umpleby's argument and undertook to show that the peneplain is younger than Eocene and is probably post-middle Miocene. Umpleby[2] replied, maintaining his original view, and for a time the matter rested. It was revived, however, when Atwood[3] published a paper on the Butte district in Montana and the Bingham district in Utah, in which he accepted Umpleby's view and made use of it in a study relating to ore enrichment. This paper drew forth further criticism by Blackwelder[4] along the lines of his earlier contention and elicited a reply from Atwood,[5] in which the latter adhered to the Eocene view. Rich,[6] the next participant in the discussion, gave a critical review of the evidence set forth by Umpleby, Atwood, and Blackwelder, with additional arguments of his own, and strongly coincided with Blackwelder's view of post-middle Miocene age for the peneplain. Rich's paper called forth remarks from Lindgren[7] and Livingston,[8] both of whom advanced data in support of the Eocene age of the peneplain. Thus the controversy rests. The writer would not disturb it except for the fact that certain aspects of it bear upon the interpretation of the erosional history of southeastern Idaho, which is a part of his present task (see Fig 1).

EOCENE VIEW

The existence of the peneplain, or at least of an old erosion surface, is recognized by all geologists who have worked in the general region. Its Eocene age is assumed by Umpleby because basins

[1] Eliot Blackwelder, "The Old Erosion Surface in Idaho: A Criticism," *ibid.*, pp. 410–14.

[2] J. B. Umpleby, "The Old Erosion Surface in Idaho," *ibid.*, Vol. XXI (1913), pp. 224–31.

[3] W. W. Atwood, "The Physiographic Conditions at Butte, Montana, and Bingham Canyon, Utah, When the Copper Ores in These Districts Were Enriched," *Econ. Geol.*, Vol. XI (1916), pp. 697–740.

[4] Eliot Blackwelder, "Physiographic Conditions and Copper Enrichment," *ibid.*, Vol. XII (1917), pp. 541–45.

[5] W. W. Atwood, "Physiographic Conditions and Copper Enrichment," *ibid.*, pp. 545–47.

[6] J. L. Rich, "An Old Erosion Surface in Idaho: Is it Eocene?" *Ibid.*, Vol. XIII (1918), pp. 120–36.

[7] Waldemar Lindgren, "The Idaho Peneplain (Discussion)," *ibid.*, pp. 486–88.

[8] D. C. Livingston, "The Idaho Peneplain (Discussion)," *ibid.*, pp. 488–92.

containing Miocene "lake beds" now lie within it, and he thinks that these basins were eroded after the development of the peneplain. He attaches considerable importance to supposed former shore lines in these basins, indicated by the position of the lake beds. A number of the basins now occupied in part by the lake beds are crossed by streams which enter and leave by steep-sided gorges. These gorges are attributed by Umpleby to headward erosion by the

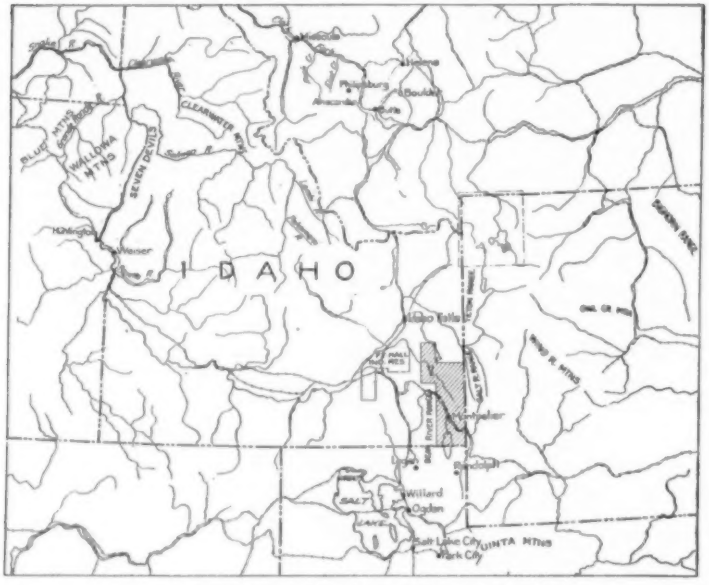

FIG. 1.—General map of southern Idaho and related areas

streams. The lake beds at exceptional places are considerably deformed but Umpleby notes that faulting and folding have also affected the plateau area, though they have not destroyed its plateau character, which has persisted in a remarkable degree.

Atwood in his discussion of conditions about Butte uses much the same arguments as Umpleby for the age of the peneplain. In his reply to Blackwelder he points out that no evidence of peneplanation of the Oligocene and Miocene sediments has been found

and he cites the lake-shore features reported by Umpleby. As evidence, which he considers most helpful in the discussion, he mentions the occurrence of stream-cut notches in some of the ridges, excavated to depths of 500 feet or more below the peneplain and partly filled with Tertiary sediments.

Lindgren, upon consideration of the criticisms of Blackwelder and Rich remarks that nobody has a right to assert the Pliocene or Miocene age of the high peneplain, who has not critically examined the relations of the Columbia River lava to that surface as exposed in the region of the western margin of the Clearwater Mountains. There the Columbia River lava extends as a beautifully developed plateau at an elevation of about 4,000 feet in front of the Clearwater Mountains. The age of the Columbia River lava, according to Lindgren, is generally conceded to be Miocene and is certainly not younger. To the east of this the Clearwater Plateau rises to elevations of 7,000 feet above the sea. Lindgren thinks the crucial point of the argument is the Miocene or pre-Miocene age of the basalt flows. Until that can be disproved he considers the age of the peneplain as Eocene or older.

Livingston also defends the Eocene age of the peneplain on the basis of the Miocene age of the Columbia River basalt. He points out that the drainage of the basalt plateau in northern Idaho, where the plateau borders mountains composed of older rocks, is in a much more youthful condition than it is in the adjacent areas of older rock. Between the heads of the canyons and the mountains the streams flow on the surface of the plateau in shallow, alluvial valleys in wind-blown silt that covers the plateau. In the mountains the streams follow more mature valleys than those cut through the basalt. Livingston thinks it inconceivable that the adjacent mountain country could have been reduced to a peneplain and the peneplain elevated and eroded to a condition of maturity, while the drainage system of the adjacent plateau did not advance beyond the condition of youth. The irregularities of present drainage, including the backward pointing of certain tributaries of Salmon River where they join the main stream, do not, he thinks, indicate an earlier drainage system intrenched by the elevation of the peneplain. He considers the Payette, Pahsimeroi, Lemhi, and some other valleys

as structural valleys, which represent the northward extension of the block faulting of the Great Basin, which is supposed to be late Miocene or early Pliocene. If this idea is correct he sees no reason why the Salmon River should not be antecedent to the structure and should not have cut the deep canyon between Pahsimeroi and Lemhi creeks while the folding and faulting were taking place.

Pardee, who has worked in the region about Philipsburg in western Montana and in the Blue Mountains of Oregon, has recognized[1] an old erosion surface which he regards as older than the Tertiary "lake beds," which now occupy the numerous, broad valleys among the mountains. In the Drummond, Sapphire, Philipsburg, and Bonner quadrangles, Montana, there are well-defined remnants of an old dissected peneplain now warped. The basin-like valleys contain Tertiary beds and the streams now enter and leave these

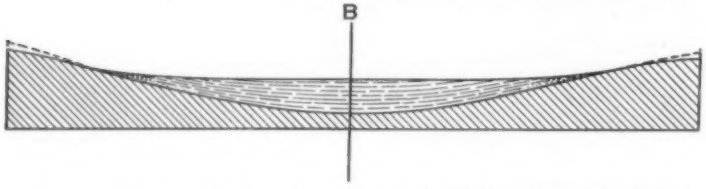

FIG. 2.—Diagram showing the structure of certain tertiary lake beds in Montana.

basins through deep canyons. A good example is Rock Creek in the Sapphire and Bonner quadrangles. The slope of the peneplain in this instance is now such that were the original surface restored the stream could not flow upon it in its present path. Pardee thinks that the course of the stream was antecedent to the warping and that the warping was slow enough to enable the downcutting of the stream to keep pace with it. The warping of the peneplain, according to his view, caused the ponding of the waters, which escaped at the lowest point in the rim of the basin thus formed. Thus changes in drainage were brought about, among which was the development of the canyon through which Flint Creek now escapes from Philipsburg Valley. Lake beds were deposited in the downwarping basin. They are now horizontal in the central portion of the basin but dip gently upward toward the margins, as shown in Figure 2. The lake

[1] J. T. Pardee, personal communication.

beds are composed largely of fine material, chiefly of pure volcanic ash and of volcanic ash mixed with sand. Only the marginal phases are at all coarse and these only moderately so, the pebbles having a maximum diameter of 3 or 4 inches and consisting of local materials.

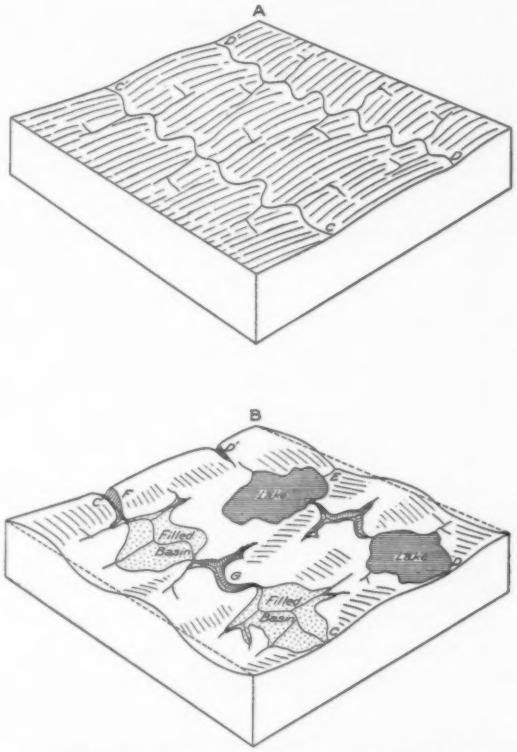

FIG. 3.—Diagrams showing the warping of a peneplain and the development of lake basins and of antecedent and diverted drainage: *A*, Peneplain with parallel adjusted streams *CC'* and *DD'*; *B*, Same warped; *DD'* has been diverted at *E* and *CC'* has become antecedent at *F* and *G*.

The beds contain Miocene fossils. The grades of the country surrounding the basin were apparently gentle at the time of the deposition of the sediments. The conditions described above are illustrated in Figure 3.

Pardee finds that the lake beds in a given basin maintain a fairly constant upper level, above which there is old soil on the older rocks. There is no sign of isolated patches of lake beds at higher levels. No actual shore features are now preserved. The present benches very gently truncate the upper slopes of the lake beds or appear practically to coincide with the upper surface of the beds. In some basins faulting has occurred at one side or the other and the lake beds are sharply tilted near the fault. In the Blue Mountains, according to Pardee, a former center of outward drainage had Miocene lake basins developed in streams outflowing from it. The relief of the region was gentle. Basalt outflowed and overspread the lake beds and some of the lower hills but did not cover all of them. Later drainage from the same areas has developed in a similar arrangement.

POST-MIDDLE MIOCENE VIEW

Blackwelder and Rich, who uphold this view, have not had an opportunity to study the peneplain question in the districts described by Umpleby, Lindgren, Livingston, and Pardee, though Blackwelder has spent ten or twelve field seasons in the Rocky Mountains, "including districts immediately adjacent to those discussed by Mr. Atwood."

Blackwelder, while recognizing the possibility that the lake beds may have been deposited in valleys eroded in the peneplain, suggests two alternative hypotheses. The first is that weak Tertiary beds may have been "down-folded or down-faulted between masses of harder rock and subsequently eroded to lowlands on account of difference of resistance to denuding process." The second is that "the broad valleys occupied by the sediments were excavated and filled before the old peneplain was made." These views are illustrated in Figure 4. Under either hypothesis the peneplain would be younger than the Tertiary beds, which would be remnants of a blanket-like deposit, which formerly overlay all but the higher ridges. From the degree of disturbance of the Tertiary beds Blackwelder is inclined to favor the first of the two alternatives. He finds it "difficult to see how any Eocene peneplain could retain an approximately horizontal attitude and nearly uniform elevation over a large part of two or more states, while sediments that have been

subsequently deposited upon it were tilted, folded, and faulted to this extent."

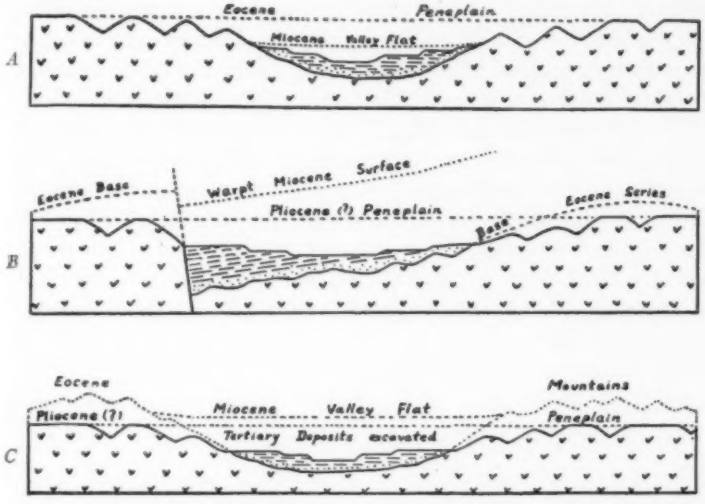

FIG. 4.—Hypotheses of Tertiary peneplanation in Idaho. After Blackwelder.

A. An Eocene plain cut across folded Cretaceous and older rocks. Later broad and deep valleys were excavated and then partly filled with Oligocene and Miocene sediments. In still more recent time streams have partly dissected the filling (essentially Mr. Atwood's conception.)

B. An early Tertiary surface, either plain or hilly, on which a thick series of Tertiary sediments was deposited. Afterward the region was gently folded and faulted so that the Tertiary beds were left alternately above and below base-level. In post-Miocene times a period of comparative quiescence permitted the cutting of a plain over the entire district, but some of the weak Tertiary deposits were preserved because they were far below base-level. In consequence of a later uplift streams rapidly excavated and planed the Tertiary deposits down to a new base-level and at the same time carved canyons and ravines in the harder rocks adjacent.

C. A broad, deep valley was excavated early in the Tertiary period and then more or less completely filled with Oligocene and Miocene deposits. The region was thereafter reduced to a peneplain, but a part of the Tertiary deposits were so far below base-level that they could not be removed. Subsequent rejuvenation of the region permitted the streams to intrench the Tertiary beds quickly and reduce them to a new plain, while the harder rocks adjacent were carved into mature topography with occasional remnants of the peneplain. On this hypothesis deformation of any kind is eliminated.

Rich's paper is a critical study of the evidence presented by Umpleby and Atwood, the results of which lead him to reject the

Eocene view and adopt instead the hypothesis favored by Blackwelder. In view of the emphasis placed by some upon the supposed Miocene age of the Columbia River lavas it is well to note Rich's comment that "the old erosion surface of supposed Eocene age is as well developed, with as large flat areas on the summits, across the supposedly Miocene lavas as it is elsewhere, and at the same levels." He explains the course of Salmon River with reference to the Lemhi and Pahsimeroi basins as a result of superposition from a peneplain developed after these basins were formed and filled. Similarly he considers that the stream-notches, now partly filled with Tertiary sediments, described by Atwood in some Montana ridges, were cut and filled before peneplanation and were later partly re-excavated. It may be noted in this connection that Smith[1] some years ago recognized a peneplain in the northern Cascades, which he assigned to the Pliocene.

DISCUSSION

The clear reasoning of Blackwelder and the critical analysis of Rich seem at first sight so convincing that apparently little would remain to be said in favor of the Eocene age of the peneplain. However, some of the geologists who are familiar with the fields of northern and central Idaho and of western Montana still feel that there are difficulties in the way of acceptance of post-middle Miocene age and that the Eocene view is not without the support of sound field evidence.

Much is made by Blackwelder and Rich of the apparent discordance between the disturbed Tertiary beds on the one hand and the relatively undisturbed peneplain on the other. But proponents of the Eocene view feel that too much emphasis is placed on discordance of attitude and not enough on accordance, and that on the whole the dislocations suffered by the peneplain are comparable with those suffered by the Tertiary beds, when the differences in the character of the rocks involved in the movements are considered. According to Pardee, there are many places like Philipsburg Valley, where the warped surface of the peneplain appears to pass beneath

[1] G. O. Smith, "Geology and Physiography of Central Washington," *U.S. Geol. Survey Prof. Paper 19* (1903), pp. 38, 39.

the gently dipping or horizontal lake beds, as if these beds were laid down in hollows progressively deepened by warping of the peneplain. If Livingston's view of the origin of certain valleys mentioned above is correct, it seems highly probable that lake beds forming in these valleys might suffer more or less dislocation during the progressive diastrophic movements to which the valleys were subjected.

The evidence of shore lines as cited by Umpleby and Atwood for the Tertiary lake basins is apparently completely discredited by Rich. Nevertheless, in the light of Pardee's observations they are not satisfactorily disposed of. To be sure no actual shore features are now preserved. Such features are geologically evanescent, but the general accordance of level of the lake-bed surfaces in many of the basins, together with the nearly horizontal attitude of the beds and the total absence of lake-bed remnants above that level, lends strong support to the view that these old lake-bed surfaces actually represent very nearly the original surface of the deposits. It may be argued that the present upper surface of these beds marks simply an erosion stage in the process of excavating the formerly completely filled valleys. On the other hand until some remnants of the former filling or blanket are found at higher levels such large scale excavation cannot safely be assumed. From the relatively weak nature of the Tertiary beds, as compared with neighboring older rocks, it would hardly be expected that their surface could withstand erosion from the Miocene to the present, but if they stood near base-level for much of that interval little erosion could occur until that condition was changed.

Blackwelder argues from his observations in Wyoming, and probably with considerable justification, that large masses of Tertiary sediments, chiefly of fluviatile origin, have been swept away from surfaces or valleys, which they once covered or filled. These sediments thus once formed a great blanket over much of the surface of the country. In southeastern Idaho it is certain from the preserved remnants that beds of this type covered much larger areas than they do at present. In northern and western Idaho and western Montana no remnants of these beds have been found above the upper level of the beds now occupying the various basins. In the absence of such remnants the former widespread occurrence of

anything like a blanket deposit of sediments may well be questioned. It seems probable therefore that there may have been important differences in the topographic development of that region and that of regions farther east and southeast.

The course of Salmon River is thought by Rich to indicate superposition from a former course upon a peneplain, which was developed over both the hard older rocks and the weaker Tertiaries. This would be a satisfactory explanation, granting the existence of such a peneplain. Livingston and Pardee would find an equally satisfactory explanation in the idea of an antecedent stream maintaining its course over a progressively warping or otherwise dislocating surface of an older peneplain in which the waters in the developing hollows became ponded. Umpleby's idea of headward erosion is discredited by Rich and is probably inapplicable.

Rich remarks that the Eocene peneplain, as described by Umpleby, "is as well developed, with as large flat areas on the summits, across the supposedly Miocene lavas as it is elsewhere, and at the same levels." This raises the question of the age of the Columbia River lavas, which Lindgren writes is the crux of the problem. If, as Umpleby[1] states, "all the lavas occupy valleys developed after the elevation of the Eocene erosion surface" and "date from late Oligocene or early Miocene to about the close of the Pliocene," Rich's criticism seems well taken. Some of the lavas of the Columbia River region, however, are of Eocene age as recognized by Smith[2] and Lindgren[3]. Thus, if the lava mapped at peneplain levels by Umpleby should prove to be Eocene, Rich's objection would have little weight. The presence of Eocene lavas and of lavas of later date than Miocene in the region, as recognized by both Umpleby and Lindgren, throws doubt on any general assumption of Miocene age for the Columbia River lavas. To be sure many of the lavas, from their association with fossiliferous sediments, are known to be Miocene, but in other instances lavas which occupy critical positions with reference to peneplain discussions are not

[1] J. B. Umpleby, "Geology and Ore Deposits of Lemhi County, Idaho," *U.S. Geol. Survey Bull. 528* (1913), p. 48.

[2] G. O. Smith, "Mount Stuart Folio," *U.S. Geol. Survey Folio 106* (1904).

[3] Waldemar Lindgren, "Silver City Folio," *U.S. Geol. Survey Folio 104* (1904).

associated with sediments of known age, and the assumption of Miocene age for these is hazardous.

The sediments themselves afford at times conflicting evidence with regard to age. Thus the Payette formation, which was at first regarded as Miocene, was later referred by Knowlton to the Eocene on the basis of floral evidence. It now seems likely that this reference may need to be changed once more, and since the age of this formation has been used as evidence of the early Tertiary or pre-Tertiary age of the peneplain, the bearing of such a change is manifest. Buwalda[1] writes regarding erosion surfaces in Idaho:

> Since the age of peneplains is determined so largely through the ascertaining of their relations to strata whose age is known, the finding of vertebrates in the supposedly Eocene at Payette last summer (1920) will aid considerably in dating these physiographic features. It can not yet be stated with certainty that the Payette is throughout younger than Eocene, but certainly large parts of it are middle or upper Miocene and some parts are apparently lower Pliocene. The effect of this evidence is obviously to make the surfaces younger than has previously been supposed.

If Buwalda's views are substantiated the difficulties regarding the age of the so-called Idaho peneplain may largely disappear. In the meantime it is well to emphasize a point brought out earlier in the discussion, namely, that there may have been important differences in the topographic development of the region including western and northern Idaho and adjacent parts of Montana and the region of southeastern Idaho and western Wyoming or other parts of the western mountain region. Atwood expresses the idea well when he says:

> I have given up the thought that there was one period of widespread peneplanation when the entire Cordilleran region was near to base level, and now favor the working hypotheses that while certain regions were high, others were low, and the relief has been different in degree, yet of the same general type that we now have in the Cordilleran provinces.

EVIDENCE OF SOUTHEASTERN IDAHO

According to present knowledge the Eocene history of southeastern Idaho is largely a record of erosion. During the epoch of Wasatch deposition, which came between earlier and later epochs

[1] J. P. Buwalda, personal communication.

of erosion, grades for a time were steep, but throughout the Green River and Bridger epochs the grades were low and it is not unlikely that southeastern Idaho thus stood near base-level. This condition seems to have lasted until the middle Miocene when orogenic disturbances were general throughout the Cordilleran region. There seems thus to have been ample time for the development of a peneplain or at least a very old erosion surface before that disturbance.

The formation of valleys in the uplifted peneplain would fall naturally in the late Miocene and may have been continued into the Pliocene. There was time enough for the opening of the broad valleys in which the Salt Lake formation was laid down and for the deposition of that formation before the close of the Pliocene. The deformation at the close of the Pliocene and the erosion and minor deformative movements of the early Pleistocene seem sufficient to account for the observed erosion stages which have been described elsewhere.[1] The table there given is repeated here for reference (Table I).

If peneplanation of the region was subsequent to the deposition of the Salt Lake formation, as would be necessary under the hypothesis favored by Blackwelder and Rich, the time allowable for that process, though perhaps sufficient, is considerably less than under the previous supposition. Moreover, a large share of erosional history in the development of the successive stages mentioned above must be crowded into the early Pleistocene.

If the peneplain were developed across the Salt Lake formation as well as over the harder and older rocks, it would seem that some patches of that formation might be found preserved at or near the peneplain level. No such remnants have been found, however. The highest patch of Salt Lake sediments thus far recognized lies on the west flank of Red Mountain in the Montpelier quadrangle and attains a maximum elevation of about 7,850 feet. It has variable dips, ranging as high as 63°, and lies just below the general level of the Gannett erosion surface. It seems to be a fluviatile deposit formed in a valley, either carved in that surface or of earlier date. For reasons which cannot be enumerated here it is tentatively

[1] G. R. Mansfield, "Geography of Southeastern Idaho." Paper read before Association of American Geographers at Cincinnati, Ohio, December 29, 1923.

assigned to an epoch intermediate between the Snowdrift peneplain and the Gannett erosion surface. The steep dip observed may be due to some local minor disturbance for the other dips noted at this locality are gentle. Elsewhere the Salt Lake formation is found in association with the lower erosion surfaces of the series above men-

TABLE I

TENTATIVE CORRELATION OF EROSION STAGES IN WESTERN WYOMING AND SOUTHEASTERN IDAHO

Epoch	Western Wyoming			Southeastern Idaho	
	Westgate and Branson	Blackwelder		Mansfield	
	Stages	Erosion Cycle (Largely Interglacial)	Glacial Stages	Erosion Cycles	
				Prof. Paper No.	*Bull. 713*
Recent		Post-glacial		Post-glacial	Spring Creek
Pleistocene	Late glacial and terraces		Pinedale	Blackfoot cycle St. Charles gl. episode)	Gibson
		Lenore			
	Early glacial		Bull Lake		
	Plain No. 1	Circle		Dry Fork	Putnam
			Buffalo		
	Plain No. 2	Black Rock		Elk Valley	
	Plains Nos. 3 and 4	Union Pass		Gannett	
Pliocene		Fremont		Deposition of Salt Lake formation	
		Wind R. summit peneplain			
Miocene	Reduction to peneplain by middle Tertiary	Middle Miocene deformation		Tygee cycle? Middle Miocene deformation	
		Aggradation of earlier valleys		Snowdrift peneplain	
Eocene					

tioned. It therefore seems probable that the Snowdrift peneplain was uplifted and eroded to form the Tygee erosion surface. The Salt Lake formation was deposited next. Then followed arching of the peneplain, which is indicated by a study of topographic profiles of the region, and the development of the Gannett and lower erosion stages.

According to this view the age of the Snowdrift peneplain might be pre-middle Miocene; the age of the Tygee surface late Miocene and perhaps in part early Pliocene; the filling of the broad valleys in that surface, Pliocene, and the rejuvenation and re-excavation of these valleys with the development of the Gannett and later erosion stages, early Pleistocene.

The course of Bear River south of the Preuss Range, in the Montpelier quadrangle, and north of the Bear River Range, near Soda Springs, suggests superposition. At the first-named locality there seems little reason to doubt this explanation, for patches of Wasatch sediments occur on the uplands both north and south of the river. Valleys, which are now tributary to Bear River at this locality and which still contain remnants of the Salt Lake formation, suggest that this superposition took place perhaps at the beginning of the Gannett erosion. At the second locality Bear River passes through a relatively short and narrow gorge between broad valleys on the east and west. The valley on the east side of the range contains abundant remnants of the Salt Lake formation. The valley on the western side has not been studied by the writer, but it contains conglomerates thought by Peale to be of Quaternary age, though farther south well recognized Pliocene (?) beds occur. The gap may have been cut by the outlet of a lake on the east side of the range which found the present site of the gorge to be the lowest point in its inclosing rim. The present constitution and distribution of the Salt Lake formation, however, are thought to be unfavorable to this view. Though locally composed of marls suggestive of lacustrine conditions, the formation as a whole is conglomeratic and in large part apparently of fluviatile origin. It now forms a blanket of irregular thickness that covers low hills and attains elevations greater than those at the top of the present gorge. It is thus thought that before the re-excavation of the valleys to the form they now have this blanket of Salt Lake sediments may have afforded a means for the superposition of Bear River upon a low place in the Bear River Range at about the same time as the similar event at the south end of the Preuss Range.

CONCLUSIONS

The idea of post-middle Miocene planation across earlier Tertiary and older rocks, as advocated for Idaho by Blackwelder and Rich, is not proved by the available evidence. There seems a probability that the erosional history of western and northern Idaho and of western Montana was somewhat different from that of southeastern Idaho or of western Wyoming. For southeastern Idaho the evidence seems to favor pre-middle Miocene planation succeeded by: (1) middle Miocene deformation; (2) late Miocene and perhaps early Pliocene erosion; (3) Pliocene deformation, erosion, and deposition; and (4) early Pleistocene deformation or rejuvenation and subsequent erosion. Further detailed studies are necessary before the physiographic inter-relationships of different parts of the Rocky Mountain Province, or of the Cordilleran region as a whole, may become known.

FOSSIL PLANTS AND UNIOS IN THE RED BEDS OF WYOMING

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ABSTRACT

This paper describes six species of plants, the first known from this region, comprising a large Equisetum and five Cycadophytes, associated with the shells of Unio, from the upper part of the Red beds in the vicinity of Lander, Wyoming, thus proving their continental origin and the presence of a considerable flora. The horizon is the same as that from which Williston described several Reptilia and called the Popo Agie beds. These correspond to the Jelm formation of Knight, and are probably Keuper in age.

In 1904 the late Professor Williston described[1] the following reptilia (pelycosaurs, cotylosaurs, and phytosaurs) from the Red beds near Lander, Wyoming: *Dolichobranchium gracile*, *Eubranchiosaurus browni*, *Brachybrachium brevipes*, and *Paleorhinus bransoni*. These came from a horizon 40 to 80 feet in thickness and about 200 feet below the top of the Red beds, and he proposed that this horizon should be called the Popo Agie beds from their typical exposure along the branches of Popo Agie River, southwest of Lander.

Subsequently Professor Williston expressed the opinion[2] that these beds are early Keuper in age and somewhat older than the Triassic of eastern North America (Newark series).

The Red beds of this part of the world have commonly been included in the somewhat inchoate Chugwater formation proposed by Darton[3] in 1908 and said to attain a thickness of about 1,200 feet in Wyoming, and to range in age from Permian to Triassic.

The Red bed problem is such a complex one both stratigraphically and paleoecologically that it seemed worth while to record the following items of interest concerning it. There has been a somewhat varying usage of stratigraphic terms in connection with the Red beds and somewhat confusing fossiliferous occurrences.

[1] S. W. Williston, *Jour. Geol.*, Vol. XII (1904), pp. 688–97.

[2] *Ibid.*, Vol. XIII (1905), p. 340.

[3] N. H. Darton, *Bull. Geol. Soc. Amer.*, Vol. XIX (1908), p. 432.

For example, in certain localities a Permian marine fauna (the Phosphoria fauna) has been recorded from the older Red beds. At other localities, supposed to be at nearly the same horizon, a supposedly lower Triassic marine fauna (the Dinwoody fauna) has been reported. At many places there are Red beds in the Sundance formation above marine Jurassic beds. Some geologists refer the whole series of Red beds from Permian to Jurassic to the Chugwater formation. Others would restrict this name to the beds below the Popo Agie beds of Williston.

Dr. John B. Reeside stated (in a letter) that it would appear probable that the Chugwater might properly be restricted to a prevailingly marine series of beds representing an eastward extension of the lower Triassic Woodside-Thaynes-Ankareh series, that the middle Triassic may be absent, and that the Popo Agie beds are upper Triassic in age, and continental in origin. These last are said to be unconformable on such a restricted Chugwater, and correspond to what Knight called[1] the Jelm formation.

For a couple of years now Mr. Newton H. Brown, who was instrumental in calling Professor Williston's attention to the vertebrate remains in the Popo Agie beds, and who has displayed a most commendable interest in the geology of the region around Lander, has been sending me fossil plants from these beds, and these constitute the main theme of this brief paper.

These plant remains are apparently present in large numbers in the Popo Agie beds, but the vast majority are very fragmentary, and, for the most part, so thoroughly oxidized that only the faintest sort of impressions are obtainable. However, as they constitute the first records, so far as I am aware, of the vegetation of the upper Triassic in this region they are of considerable interest.

At this same horizon shells of Unio of probably more than one species are not at all uncommon. One of these appears to me to be identical with *Unio dumblei* described by Simpson[2] from the Dockum formation of Texas. This formation is of continental origin and Triassic age according to the vertebrate remains found in it, as interpreted by E. D. Cope.

[1] S. H. Knight, *Bull. Geol. Soc. Amer.*, Vol. XXVIII (1917), p. 168.

[2] C. T. Simpson, *Proc. U.S. Nat. Mus.*, Vol. XVIII (1895), p. 383, Fig. 3.

The plant remains, described in the following pages, represent six species, only one of which is complete enough to merit a specific name. Five of these are cycadophytes and the sixth is a large species of Equisetum, which is abundant but very badly preserved. Strangely absent are any traces of either conifers or ferns, both of which are types that usually play a considerable rôle in floras of the upper Triassic. That the absence of these two types is not to be explained upon any climatic basis, is obvious from their presence in most floras of this age associated with cycadophytes which cannot be readily distinguished from those found near Lander. There is probably no phase of paleobotany in as great a state of confusion as the flora of the Triassic and this is very largely due to the unsatisfactory condition of our knowledge of cycadophyte foliage—a subject of too great magnitude and too little scientific knowledge to merit discussion in the present connection. Neither has the time arrived for attempting to draw an environmental picture from cycadophyte ecology. There has been much speculation on this subject, but very little real evidence.

With regard to the age indications of the following plants they seem to me to quite obviously indicate a Keuper or Rhaetic age, and there is some slight ground in the forms represented, and in the absence of diagnostic Rhaetic forms, to regard the age as Keuper, thus agreeing substantially with the evidence of the associated vertebrate remains. There is no ground for an opinion as to whether this is early or late Keuper, and I have not thought it worth while to discuss this evidence as to age apart from the description of species that follow.

EQUISETUM SP. (Fig. 1)

At certain outcrops of the Red beds there is a large amount of broken fragments of flattened stems of a large Equisetum. This is too poorly preserved for identification or proper diagnosis. There are some traces of coaly matter in some of the specimens. More frequently there is more or less of a ferruginous replacement.

The maximum width of flattened fragments in the material seen is 10 centimeters and one large specimen shows a relatively short internode 4 centimeters in length. The ribs in the larger specimens are flatly arched and about 2 millimeters wide, separated

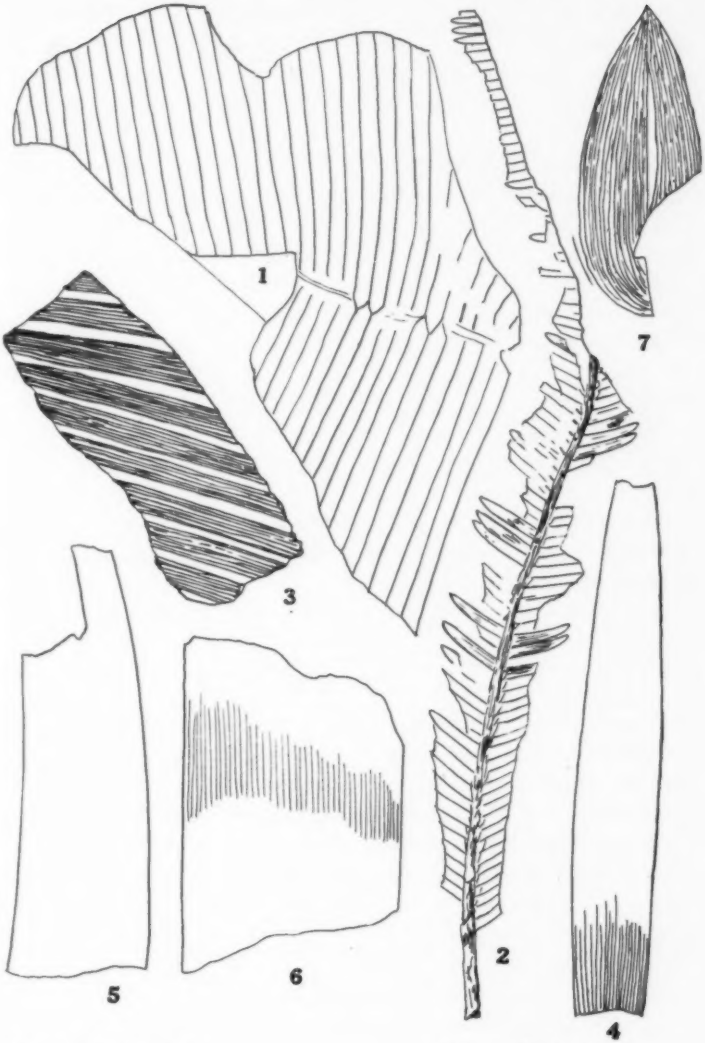

FIG. 1.—*Equisetum* sp.
FIG. 2.—*Pterophyllum Browni* Berry, n. sp.
FIG. 3.—*Pterophyllum* (?) sp.
FIG. 4.—*Zamites* sp.
FIGS. 5, 6.—*Zamites* (?) sp.
FIG. 7.—*Podozamites* sp.

by narrow, deep, rounded grooves. Much of the material shows the counterpart of this condition with narrow elevated ridges and flat grooves as in the specimen figured. The ribs alternate at the nodes but no details can be made out and there are no traces of sheaths observable.

This species is about the same size as *Equisetum Rogersi* (Bunbury) Schimper[1] which is not uncommon in the rocks of the Newark series of eastern North America from New Brunswick to North Carolina, and is especially abundant in the Richmond area of Virginia. I should not be surprised if the Wyoming plant represented this species with the sheaths detached.

In the European floras the larger Equisetums are more especially characteristic of, although by no means confined to, the earlier Triassic. Among comparable forms from that continent are *Equisetum arenaceum* (Jaeger) Bronn, and *E. platydon* Brongniart, the latter a very widespread and variable form. Both are from the Keuper.

Fontaine described[2] two large species of Equisetum from the Triassic of Abiquiu, New Mexico, but neither of these appears to be identical with the Wyoming plant.

Divide between Willow Creek and Little Popo Agie River, Wyoming.

PTEROPHYLLUM BROWNI BERRY N. SP. (Fig. 2)

Fronds elongate, slender, stipitate, pectinate. Pinnules inserted by their whole base on the sides of a stout rachis, closely spaced, diverging from the rachis at wide angles, varying from 55° to 75°; about five times as long as wide, with parallel margins, some of them very slightly falcate, narrowed at the tip and for the most part bluntly and unsymmetrically pointed, about 11 millimeters long and 2 millimeters wide, with a few stout, immersed, parallel, simple, longitudinal veins. Texture coriaceous. Rachis nearly as wide as the pinnules are broad.

This species is named in honor of the collector, Newton H. Brown, and it is described as new because of the conviction that

[1] For an account of this species see W. M. Fontaine, *U.S. Geol. Survey Mon. 6* (1883), p. 10, Pl. I, Fig. 2; Pl. II, Figs. 1, 2.

[2] W. M. Fontaine, *U. S. Nat. Mus., Proc.*, Vol. XIII (1890), p. 283, Pls. XXII–XXIV.

it is most dangerous, and against the best interests of paleobotany to hazard long range correlations with similar forms described from distant areas and perhaps different geologic horizons.

Among previously described fossil species there are a number which closely approach the present species in appearance. Perhaps the most similar, if one may draw conclusions from the notoriously inaccurate figures of Fontaine, is a form from the Triassic of Virginia which this author[1] referred to the British species *Ctenophyllum taxinum* (Lindley and Hutton).[2] The Wyoming plant is less like the English type, which came from the Stonesfield slate, and has less closely spaced, more slender and more tapering pinnules. The Virginia material has a stouter rachis, more ascending and more obtusely tipped pinnules.

Schimper[3] proposed the genus Ctenophyllum for cycadophyte foliage in the form of linear fronds with the pinnules attached obliquely to the upper side of the rachis; the pinnules being linear, obtuse, decurrent at the base, and with delicate parallel veins. Most of the forms referred to this genus, especially numerous ones recorded by Fontaine, should be referred to Pterophyllum. Certainly the Virginia plant appears to be excluded from the genus Pterophyllum in having the pinnules attached laterally along the rachis and in lacking decurrent bases.

Other very similar appearing forms are *Pterophyllum imbricatum* Ettingshausen[4] and *Zamites gracilis* Andrae[5] from the lower Lias of Transylvania, and there is also a similarity, less close however, to *Pterophyllum Meriani* Heer from the Keuper of Switzerland, and to the smaller forms of *Pterophyllum Jaegeri* Brongniart, recorded by Leuthardt[6] from the last horizon.

Still other comparable forms are some of the Jurassic varieties wrongly named *Williamsonia pecten* (L. & H.), *Pterophyllum*

[1] W. M. Fontaine, *U.S. Geol. Survey Mon. 6* (1883), p. 67, Pl. XXXIII, Figs. 3–4*a*.

[2] Lindley and Hutton, *Fossil Flora Great Britain*, Vol. III (1835), p. 65, Pl. CLXXV (under Zamia).

[3] W. P. Schimper, *Pal. Végét.*, Tome II (1870), p. 143.

[4] C. von Ettingshausen, *Abh. k. k. geol. Reichs.* Bd. I (1852), Ab. 3, Nr. 3, p. 7, Pl. I, Fig. 1.

[5] C. J. Andrae, *Foss. Fl. Siebenbürgen und des Banats* (1855), p. 40, Pl. XI, Figs. 4, 5.

[6] F. Leuthardt, *Die Keuperflora von Neuewelt bei Basel* (1903), Pl. V, Figs. 1–3.

contiguum Schenk of the Rhaetic[1] of eastern Asia, and *Zamites (Pterophyllum) Rolkeri* Newberry[2] from the supposed Rhaetic of Honduras. The last has shorter and narrower pinnules.

The foregoing comparisons, admittedly of slight value, tend to confirm the general impression conveyed by the other Papo Agie plants that the age is upper Triassic.

The type comes from an outcrop 2 miles southwest of Lander, Wyoming.

PTEROPHYLLUM (?) SP. (Fig. 3)

The generic relationship of this form is not conclusive. It is probably a Pterophyllum, but might represent some narrow pinnuled species of Zamites. There are several specimens like the one figured showing these narrow linear-lanceolate pinnules arranged regularly side by side in the rock. The fact that they narrow in only one direction suggests that they represent a Pterophyllum, although nothing is known of their position of attachment on the rachis and they might represent a Ptilophyllum.

The largest pinnule is 7 millimeters in maximum width and the length must have been at least 7 or 8 centimeters. The texture is coriaceous. The veins are simple as far as known, longitudinal and parallel, and 10 per pinnule.

The locality is Squaw Creek, northwest quarter of Sec. 21, T. 33, R. 100.

These fragments represent a type of cycadophyte foliage that is especially characteristic of the upper Triassic. Naturally such fragmentary material shows resemblances to a considerable number of cycadophytes with narrow elongated pinnules. Among these the following may be mentioned as showing rather great similarities to the present species in so far as the features of the latter can be made out.

Among North American forms these comparable species are *Zamites occidentalis* Newberry[3] from the Triassic of Abiquiu, New Mexico, in which the pinnules are shorter: *Pterophyllum*

[1] R. Zeiller, *Fl. Foss. Gites Charbon Tonkin* (1903), p. 191, Pl. XLVIII, Figs. 1–8.

[2] J. S. Newberry, *Amer. Jour. Sci.* (3), Vol. XXXVI (1888), p. 343, Pl. VIII, Figs. 1, 2.

[3] J. S. Newberry, *Rept. Macomb Expl. Exped.* (1876), p. 142, Pl. V, Figs. 1, 2.

inaequale Fontaine[1] from the Newark rocks of Virginia; *Podozamites longifolius* (Emmons)[2] from the Newark of North Carolina; the form from the Newark of Pennsylvania that Fontaine[3] identified as *Dioonites carnallianus* (Goeppert) Born.; and the form from the Newark of North Carolina that Fontaine[4] identified as *Ctenophyllum braunianum angustum* (Braun) Schimper.

Among non-American forms it may be compared with *Pterophyllum longifolium* Brongniart from the Keuper of Neuewelt in Switzerland;[5] *Pterophyllum Jaegeri* Brongniart from the Keuper of Stuttgart, Neuewelt and Lunz;[6] and *Pterophyllum aequale* (Brongniart) Nathorst from the Rhaetic of Sweden, Tonkin,[7] and China.

ZAMITES SP. (Fig. 4)

This cycadophyte is represented by the incomplete linear-lanceolate pinnules of which the most complete is the one figured. These are somewhere in the neighborhood of 12 or more centimeters in length and 1.4 centimeters in maximum width, with an acute tip and a contracted base. The texture is coriaceous. The veins are stout, but not conspicuous, simple, longitudinal, parallel, and about twenty-five in number.

This obviously represents some species properly referable to the genus Zamites as the latter is understood at the present time. The material is so incomplete that it is futile to attempt comparisons with previously described forms. Among these it resembles somewhat the form from the Newark series in Pennsylvania, Virginia, and North Carolina that Fontaine described[8] as *Ctenophyllum grandifolium*. It differs from the latter in having the

[1] W. M. Fontaine, *U.S. Geol. Survey Mon. 6* (1883), p. 64, Pl. XXXVI, Fig. 1.

[2] W. M. Fontaine, *U.S. Geol. Survey 20th Ann. Rept.*, Pt. II (1900), p. 294, Pls. XL, XLI.

[3] *Ibid.*, p. 244, Pl. XXVIII, Fig. 2.

[4] *Ibid.*, Pl. XXXIX, Figs. 6, 7.

[5] F. Leuthardt, *Keuperflora von Neuewelt* (1903), p. 16, Pls. V–X.

[6] *Ibid.*, p. 14, Pl. V, Figs. 1–3; Pl. VI, Figs. 1, 2; Pl. X, Fig. 1.

[7] R. Zeiller, *Fl. Foss. Gites Charbon Tonkin* (1903), p. 194, Pl. XLIX, Figs. 4–7.

[8] W. M. Fontaine, *U.S. Geol. Survey Mon. 6* (1883), p. 73, Pl. XXXIX, Figs. 1–3; Pls. XL, XLI; Pl. XLII, Fig. 1.

pinnules distinctly narrowed proximad. Fragmentary material is not uncommon at the outcrop 4 miles southwest of Lander, Wyoming.

ZAMITES (?) SP. (Figs. 5 and 6)

This species was a large fronded cycadophyte of uncertain relationships. It is the commonest plant in the Red beds around Lander but is invariably preserved as faint and fragmentary specimens. Two typical fragments are figured. They indicate pinnules of large size—the largest fragment shows a width of 3.8 centimeters. The parallel longitudinal veins are simple in all of the fragments which, however, are from the medial part of the pinnules. There are twenty-six of these veins per centimeter of width. The texture appears to have been fairly coriaceous, but less thick than in the associated Zamites sp. It is possible that these remains represent the medial portion of pinnules of some large *Sphenozamites* like *Sphenozamites rogersianus* Fontaine[1] which is so common in the Newark beds of Virginia and is recorded from these beds in Pennsylvania and North Carolina. They also suggest what Fontaine described as *Ctenophyllum giganteum* from these same beds in Virginia.[2]

They come from an outcrop 2 miles southwest of Lander, Wyoming.

PODOZAMITES (?) SP. (Fig. 7)

Pinnule relatively short and wide, ovate in general outline, with an acute tip and a broadly rounded base. Length about 5.25 centimeters. Maximum width, slightly below the middle, about 2.25 centimeters. Texture coriaceous. Veins thin, numerous, longitudinal, subparallel with one another and with the pinnule margins.

I know of no better reference for this incomplete specimen than the somewhat doubtfully allocated genus Podozamites, which often has fronds with similar short and wide pinnules. No previously described fossil that has come to my attention is especially close to the present form. It is somewhat like *Podozamites stonesfieldensis*

[1] W. M. Fontaine, *U. S. Geol. Survey Mon. 6* (1883), pp. 80, 98, Pl. XLIII, Fig. 1; Pl. XLIV, Figs. 1, 2; Pl. XLV, Figs. 1, 2; Pl. XLIX, Fig. 4.

[2] *Ibid.*, p. 76, Pl. XXXIX, Fig. 5.

Seward[1] of the Stonesfield slate of England in which, however, the pinnule is somewhat larger and has a much coarser venation. It is also similar to *Podozamites crassifolia* Newberry[2] from the Triassic of Los Bronces, Sonora, but the Wyoming form is relatively wider and more pointed. Similar or identical with Newberry's species is the variety of the European Rhaetic form *Zamites distans* Presl. which Schenk[3] called *latifolia* (*Zamites subovatus* Münster).

The specimen comes from 4 miles southwest of Lander, SW ¼, Sec. 27, T. 33, R. 100.

[1] A. C. Seward, *Jurassic Fl.* (1904), Pt. II, p. 121, Pl. XI, Figs. 1, 2.

[2] J. S. Newberry, *Rept. of Macomb Exp. Exped.* (1876), p. 145, Pl. VI, Fig. 10.

[3] A. Schenk, *Foss. Fl. Grenzschichten Keupers u. Lias Frankens* (1867), p. 159, Pl. XXXVI, Figs. 1–3.

A NOTE ON THE LANCASTER GAP MINE, PENNSYLVANIA

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ABSTRACT

A series of observations, both of the field relations and of the microstructure of this nickel ore-body, are recorded. The igneous theory of the origin of the deposits is brought into question and a hydrothermal view of the genesis put forward.

INTRODUCTION

In his paper on the Gap mine, Kemp[1] has put forward as a possible theory of origin of the deposit the view that it is the result of a differentiation *in situ*. The Soret principle is appealed to as the method of differentiation. Since the time when this article was written it has been shown that, even with a temperature difference of 100° between two points in a magma, the difference in concentration would be almost negligible. In view of this fact it was thought that a visit to the mine and its neighborhood might furnish some further light on the genesis of this nickel ore-body. The following is the result of an excursion to the district in the fall of last year.

The Lancaster Gap Mine lies about 15 miles to the east of Lancaster, Pennsylvania. By road it is 4 miles south of Kinzer, which is on the main line of the Pennsylvania railroad. The surrounding country presents a subdued topography of low hills and valleys.

The last mining was done in 1900, so that the workings were full of water when visited. Through the kindness of Mr. C. Doble, the former superintendent of the mine, the writer was able to ascertain the nature of the occurrence and distribution of the ore and also to collect typical specimens.

[1] J. F. Kemp, *Trans., Amer. Inst. Min. Eng.*, Vol. XXIV (1894), pp. 622–31.

ROCKS ASSOCIATED WITH THE ORE

The rock in the vicinity of the mine is mica schist. The mica is very abundant, and the rock weathers easily *in situ* to a white sand, which often retains traces of the original foliation. Throughout the neighborhood the schist is cut by quartz veins and by pegmatites. The quartz of the veins does not always show the milky appearance common in vein quartz, but is frequently clear and transparent. Intergrown with the quartz there occur large plates of muscovite. The appearance here is very similar to the intergrowths of quartz and mica seen in pegmatites. It is probable that the quartz veins and the pegmatites are contemporaneous and that the one grades into the other.

One of the most remarkable features of the district is the occurrence, in the mica schist, quartz veins, and pegmatites, of large tourmalines. These latter reach exceptional dimensions, some being as long as 3 inches and with a thickness of $\frac{3}{4}$ of an inch. In the schists they are distinctly later than the development of schistosity since they cut across the latter in a quite irregular manner. In the quartz veins and in the pegmatites they have formed during the crystallization and were fractured by the directed pressures existing during intrusion. In the fractures quartz crystallized, giving "stretched" tourmalines. Thin needles of hornblende also occur in the veins and pegmatites.

Usually the schists, quartz veins, and pegmatites do not contain any metallic minerals. In a few cases, however, grains of pyrite are observed. In some places these rocks are spotted with iron stains which would indicate the weathering of some highly ferruginous mineral, perhaps an iron sulphide.

The rock associated with the ore deposit is an amphibolite of an exceedingly tough character. It is entirely surrounded by schists and has a roughly lenticular outcrop, the major axis of the lens trending from east to west. This direction conforms to the major structural directions of the district as mapped by Frazer.[1] According to the latter the contact between the Archean schists and the Cambro-Silurian limestone lies a little over $1\frac{1}{2}$ miles to the

[1] P. Frazer, *Rep. CCC, Second Pennsylvania Survey.*

north and trends roughly east-west. Two and a half miles to the south of the mine there occurs another long band of limestone inclosed in the schist, and here again the direction is east-west.

The contacts of schist and amphibolite are not vertical. The dip is toward the igneous rock. At the eastern end of the intrusive it has been proved in the workings that the dip is approximately 45° to the west. On the southern contact the dip is to the north. With depth it has been found that this dip shows a tendency to be reversed, giving the schist as the hanging wall.

All the amphibolite shows signs of having been subjected to stresses. The latter have developed a jointing in the rock which made the sinking of shafts very difficult, as the rock was often in the form of huge loose blocks. These stress phenomena are more pronounced toward the west, though they are present also in the rest of the intrusive.

The other igneous rock in the district is a dolerite dyke of Triassic age.[1] It trends in a southwesterly direction and occurs two thousand feet to the south of the mine. The minerals present are labradorite, augite, and olivine. An examination of thin sections shows no trace of sulphides. The only ore mineral present is magnetite, and it may be either a primary crystallization or an alteration product of olivine. The rock does not appear to have any connection with the nickel ore-deposit.

The ore occurs mostly at the contact of schist and amphibolite. The known contact, however, is not all mineralized. To the west on the south side of the igneous rock no ore occurs, and on the northern contact the mineralization has been confined to parts of the contact. The distribution of the ore can be seen by reference to the map given by Kemp.[2]

In later mining it was found that some of the ore did not occur at the contact. About four hundred feet from the eastern boundary of the igneous rock the sulphide mass at depth was found to split into two branches. One of these broke through the amphibolite, rising about two in five in a direction 10° west of north. The other branch continued along the contact like the rest of the ore mined. Of these two branches only the former was worked. Development

[1] P. Frazer, *Rep. CCC, Second Pennsylvania Survey.* [2] *Op. cit.*

of this ore body showed that after continuing in its course for about two hundred feet it started to dip to the north. Just at this stage the mines were closed so that it is not known whether the ore cut across the amphibolite to the schist in the north side. There are other instances recorded of ore occurring in the amphibolite away from the contact. In shaft-sinking and in development work large sheet-like bodies of ore were met inclosed in amphibolite. Though frequently of moderate extent these were very narrow, sometimes only a few inches.

The width of the main ore body is variable. The maximum distance between the walls is 40 feet and the average, 20 feet. The contact with the amphibolite is everywhere gradational, and most of the rock shows some sulphide.

The contact of ore and schist on the south side is sharp. Here, also, there is a development of gouge at the contact. This gouge varies in thickness from a mere seam to several inches. In the workings on the north side there was no clear line of demarcation between the actual ore body and the schist. The latter was penetrated in mining for 15 feet and showed decided mineralization. The mineral content was not high enough to work, and so development ceased. Specimens of this mineralized schist show the presence of pyrite in cubes, pyrrhotite, and chalcopyrite. Along with these minerals black tourmalines also occur, similar to those found in the quartz veins and pegmatites of the neighborhood. At this northern ore body there has not been as great a development of gouge as in the rest of the ore.

MICROSCOPIC AND MACROSCOPIC CHARACTERS

The igneous rock consists principally of hornblende. Some crystals of that mineral show characteristic pleochroism, but others are quite colorless and can only be distinguished from pyroxene by extinction and cleavage in the proper sections. In a few cases hornblende is seen to be a uralitization product of pyroxene. At the same time it does not necessarily follow that all the hornblende of the slide has been so formed. By far the larger proportion of the amphibole shows no trace of having been formed from any primary mineral. One would expect that in so extensive a uralitization

as this it must have been that some hornblende with the crystal outlines of pyroxene would have occurred. No such phenomenon was observed and it is probable that though some hornblende is the result of alteration of pyroxene the bulk of that mineral is a primary crystallization from a magma.

Both orthorhombic and monoclinic pyroxene are present. The latter is the more abundant, the orthorhombic variety being rare. Almost all the augite present shows a certain degree of uralitization. The orthorhombic pyroxene was found in only two slides and showed no alteration.

In a few slides quartz, apatite, and feldspar occur. The latter is a calcic variety.

One of the most striking features of the rock is the occurrence of biotite. The latter is sometimes colorless and usually presents a bleached appearance. It is distinctly secondary in origin. This conclusion is reached on three grounds. In the first place, the mineral occurs in masses of shreds which cut across the primary minerals of the rock. In the midst of such masses unreplaced fragments of hornblende occur, and these fragments are optically continuous with the surrounding hornblende. Secondly, the grain size of the biotite is variable. Some shreds are so small that their true character can only be determined by the high power. Larger shreds are also present, but in no case do their dimensions exceed one quarter the average grain size of the rock, and in the majority of cases they are much smaller. This great difference in size between the biotite crystals and the other minerals of the rock indicates distinctly different conditions during the crystallization. The best explanation appears to be that the biotite is secondary. The third proof is found when the relations of the individual biotite crystals to the hornblende are considered. The former project into the latter and the direction of the flakes has frequently been determined by the cleavage of the amphibole. Figure 1 gives a camera lucida drawing showing the relations of amphibole and biotite.

METALLIC MINERALS AND THEIR RELATIONS

The metallic minerals are present as large irregular masses and as veins. In both occurrences they cut across the other minerals of the rock. In the veins the sides do not match, so that the metallic

minerals have not been deposited solely by fissure-filling. From the veins small finger-like protrusions of sulphide extend into the hornblende. The directions of these protrusions coincide in general

FIG. 1.—A camera lucida drawing showing the relations of the amphibole and biotite. The biotite varies greatly in size, the material at the foot of the field being identifiable only with the high power. In the right half a mass of sulphide occurs replacing both biotite and hornblende.

with the cleavages of the amphibole, but the boundaries are usually irregular. These veins are interpreted as replacements which have probably started from minute cracks in the hornblende. The same

relations hold for the large masses of sulphide. The minerals surrounding them have been replaced along prominent cleavages and also sometimes quite irregularly. Within the sulphides there are isolated fragments of rock minerals, and these are optically continuous with crystals lying outside. This isolation of fragments of silicate can frequently be seen only partially completed, the sulphides having cut but part way across hornblende or some other silicate. Figures 2 and 3 give photomicrographs of the characteristic relations of the sulphides and silicates.

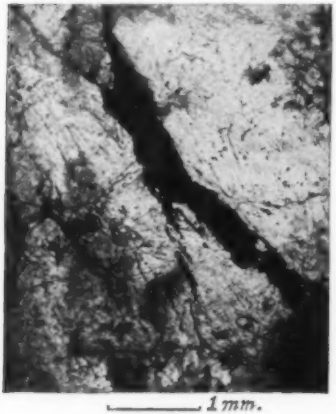

FIG. 2

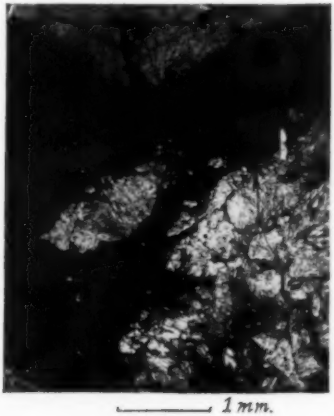

FIG. 3

FIG. 2.—A photograph of a veinlike occurrence of pyrrhotite replacing hornblende.

FIG. 3.—A photograph of the more massive type of replacement of hornblende by sulphide.

An important feature of the replacement is that the biotite, itself secondary, has also suffered during the mineralization. The replacement is particularly evident on account of the perfect cleavage of the biotite. The sulphides usually conform to these cleavages. Sometimes, however, they have cut across from one cleavage to another with the result that fragments of biotite are inclosed by sulphides. This replacement has proceeded in many of the masses of biotite shreds already described in a preceding paragraph (Fig. 1). The net result in such a case is that we have

a large irregular mass of sulphide surrounded by a fringe of biotite shreds and the whole cutting across the other minerals of the rock.

Throughout the slides examined there appears to have been a tendency for the sulphides to preferentially replace the biotite rather than the amphibole, though the latter has suffered extensively. There are also indications that the sulphide mineralization has followed closely on the introduction of biotite and, in some cases, has overlapped. In an extensively mineralized portion of a section there sometimes occur intergrowths of sulphide and biotite. The boundaries of the biotite are perfectly straight and well defined without any sign of replacement. Figure 4 gives a photomicrograph of these relations.

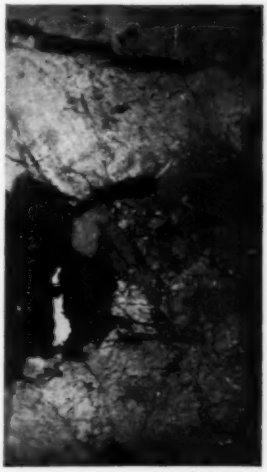

FIG. 4.—A photograph showing the relations of the sulphides and the biotite. To the left the sulphides are present as a replacement of a biotite crystal. To the right small lathlike crystals of biotite occur contemporaneously with sulphides.

The only occurrence of sulphide which might possibly be ascribed to a primary rock crystallization are small specks which are present entirely within pyriboles.[1] Even here their igneous origin is doubtful. Examination shows that almost invariably one boundary at least is controlled by the cleavage of the adjacent silicate. Further, these occurrences are always most abundant close to the large replacements by sulphides, which suggests that both are of the same origin.

Hand specimens of the amphibolite away from the ore bodies show sulphides as irregular stringers and patches. These veinlike occurrences are distinctly later than the consolidation of the rock, for they cut across crystals of hornblende. In some cases one of their boundaries may be straight and the other irregular suggesting that replacement has proceeded in one direction from a small frac-

[1] "Pyribole" is used here to comprehend amphiboles and pyroxenes.

ture. More frequently, however, both boundaries are quite irregular and small fingers of sulphide break away from the main vein and cut across the silicates. Intergrown with these veins there is calcitic siderite. This siderite is contemporaneous with the sulphides, the vein changing from sulphide to siderite without any break in its continuity. Figure 5 gives a drawing of a typical specimen.

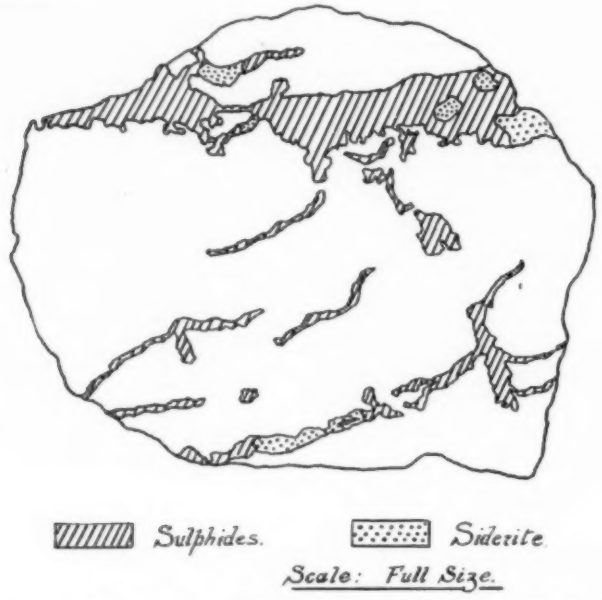

FIG. 5.—A drawing of a typical specimen of mineralized amphibolite. The siderite and sulphide relations show the contemporaneity of these minerals. The veinlike occurrences leave little doubt that the sulphides and siderite are later than the formation of the amphibolite.

The sulphides also occur as irregular patches in the amphibolite, outside the ore bodies. When such a specimen is polished it is seen that here again the sulphide bears a replacement relation to the silicates. Occasionally a straight contact of sulphide and silicate occurs, but closer examination shows that such a contact conforms to the cleavage of a hornblende or biotite crystal. By

far the more common occurrence is a most irregular contact between sulphides and rock minerals with veinlets of sulphide protruding into the silicates.

When the ore itself is examined it is found that the relations are the same as in the mineralized amphibolite. One of the characteristics of both the pyrrhotite and chalcopyrite ore is the presence in them of small fragments of amphibolite. Since the pyrrhotite weathers comparatively rapidly these fragments stand out as knobs in the weathered ore. A cursory examination of this phenomenon in the field gives the impression that these silicate masses are concretions, but in a polished specimen they are seen to be very irregular fragments of the igneous rock. Some are rounded. Besides those seen in the unpolished specimen there are also numerous smaller patches of hornblende, some of which are clearly cut off from the larger masses. Without any magnification the sulphides can be seen cutting across the silicates, and under the reflecting microscope these relations are even more apparent. The replacement of silicates by sulphides can be seen in all stages of progress. Figure 6 gives a drawing of a typical specimen and figures 7 and 8 are photographs with the reflecting microscope.

GENESIS OF THE ORES

The only theory put forward for the origin of these sulphide masses is that given by Kemp.[1] The latter makes use of the Soret principle as the method of differentiation. As mentioned at the beginning of the paper, it has been indicated that differentiation under the conditions hypothesized by this principle is incapable of giving any great concentration. Of the igneous theories now held and possibly applicable here there remain differentiation by gravitative settling of early formed crystals and differentiation by settling within a still fluid sulphide melt.

The one feature of these deposits which would seem to favor an igneous view of their origin is the fact that the contact of the ore and amphibolite is gradational in the majority of cases, while the contact with the schist is sharp. Also the amphibolite shows the presence of sulphides throughout its extent. But such a

[1] *Op. cit.*

relation can be otherwise explained. The maximum width of the amphibolite is only 500 feet. If at either side of the igneous there was present some agency capable of depositing such large sulphide masses as comprise the ore bodies it would be strange if its effects did not reach as far as 200 feet. The insurmountable difficulty to the igneous view is the actual relations of the sulphides to the amphibolite as observable both in the field and in specimens.

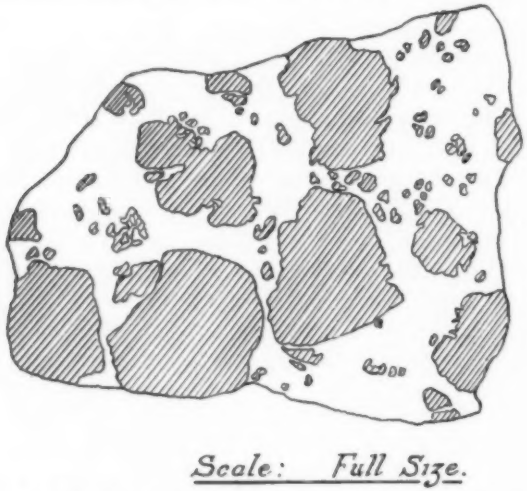

FIG. 6.—A drawing of a typical specimen of sulphide ore. The shaded material shows the form of the silicates found in the ore. The outlines of these fragments are very suggestive of replacement. Some of the now isolated particles have been formerly connected. These silicates are relics of the replaced amphibolite.

In all these occurrences the ore is distinctly later than the silicates and replaces them. This replacement has proceeded in many instances from small fractures.

In their paper on the sulphide ores Tolman and Rogers[1] have put forward the view that, in the magma, replacement of previously formed silicates by sulphide may take place by the action of mineralizers. One of the minerals especially susceptible to this replacement

[1] Tolman and Rogers, "A Study of the Magnetic Sulfid Ores," *Stanford Univ. Pub.*, University Series, 1916.

they say is biotite. Observations on the Gap ore might appear at first thought to support this special susceptibility of biotite in the magma. The relations of the biotite in this case, however, show that it is not a primary rock crystallization. It is itself clearly a replacement of the primary rock-forming minerals, and the replacement took place later than the solidification of the rock.

One of the objections offered by Kemp to a hydrothermal theory of the origin of these deposits is that the rock is by no means

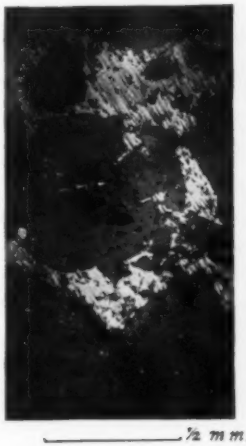

FIG. 7

FIG. 8

FIGS. 7 AND 8.—Photographs with reflected light of the relations of the silicates and sulphides. The specimens are from ore similar to that shown in Figure 6 and show the nature of the contact of the silicates and sulphides.

a rotten rock.[1] There is no necessity for extensive alteration of the hydrothermal type unless the minerals of the original rock are notably unstable under the new conditions. The factors governing the changes are pressure, temperature, and chemical stability. The minerals of the amphibolite are characteristic of high temperature and pressure. The ore is pyrrhotite associated with biotite. Both of these minerals are also characteristic of high temperature

[1] *Op. cit.*

and pressure. So far, then, as the latter two factors are concerned there is no reason why alteration should occur. When the chemical side of the matter is considered, it is seen that equilibrium between the solutions and the silicates was attained by replacement of the latter by sulphide. Where the solutions did not come in contact with the silicates the latter are therefore quite fresh.

The sequence of processes in the formation of this nickel ore-body appear to have been as follows: The rock was subjected to some form of stress. The result was not so much to cause large fissures as to develop small cracks throughout the igneous mass. This deformation was followed by the ascent of solutions along the contacts. From these solutions biotite formed by the replacement of silicates. Following this came solutions carrying sulphur, iron, copper, the carbonate radicle, and nickel. By interaction with the silicates sulphides were formed. The previously formed biotite was particularly susceptible to this replacement. The periods of biotite and sulphide mineralizations have overlapped so that in rare cases both minerals occur side by side.

When the source of the solutions is sought nothing definite can be said at present. The localization of the ores round the amphibolite would at first incline one to believe that the solutions and the igneous rock are genetically related. To this view there are several objections. Between the ore and the schist there is frequently a layer of gouge. This gouge appears to have affected the movement of the solutions since on the north side where the gouge development has been less the mineralization has penetrated the schist. Though time for this deformation could elapse and still the solutions come from the same parent source as the amphibolite, yet it leads one to entertain the possibility that between the two there is no genetic connection. One other possible theory is to connect the solutions with the quartz and pegmatite veins of the neighborhood. That these latter were high in mineralizers is evident in the presence of large tourmalines. At present, however, there is not sufficient evidence to warrant a definite conclusion.

In concluding, the writer wishes to express his indebtedness to Mr. C. Doble, on whose information most of the field observations were based, and to Professor Bastin for his advice and criticism.

FAULTING SOUTH OF BILLINGS, MONTANA[1]

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ABSTRACT

Two groups of faults are described: one near the Pryor Mountains and having a dominant north-south trend; the other 8–12 miles north of the mountains and having a trend of N. 40° E. Most of the faults of the first group are due to tension developed adjacent to the Pryor Mountains as a result of their bodily uplift during folding. All of the other faults of the area are due to some phase of adjustment of rotational strain during the mountain-building action. The rotational strain in the area resulted from greater eastward movements in the region west of the Pryor Mountains than in that northwest of them. Estimates of the amount of shortening represented in the mountain folding and of the horizontal displacement along the faults to the north indicate that compensation of the rotational strain by faulting was more than half complete.

INTRODUCTION

In the field season of 1922 the writer was employed by the United States Geological Survey in geologic work in the region south and southwest of Billings, Montana.[2] During the course of this work some faults were mapped which are believed to be of special interest because they offer opportunity for examining the mechanism of adjustment of rotational strains between the end of a line of mountain folding and a relatively undisturbed area adjacent to it. The general geologic features of the surrounding region and their relations to the area of the faulting are shown in the index map (Fig. 1). The Bighorn Mountains upfolding is seen to be a very prominent structural feature in the region south of the area of the detailed map. This mountain anticline is divided into two parts by the Bighorn River. That on the south is called the Bighorn Mountains; that on the north, the Pryor Mountains.

The structure of the region north of the Pryor Mountains presents a marked contrast to that of these mountains, for here only minor folding has been described in the several geologic

[1] Published with the permission of the Director, U.S. Geological Survey.

[2] *Oil and Gas Prospects North of the Pryor Mountains, Montana*, Preliminary report as a *Press Bulletin*, September 18, 1923, U.S. Geological Survey.

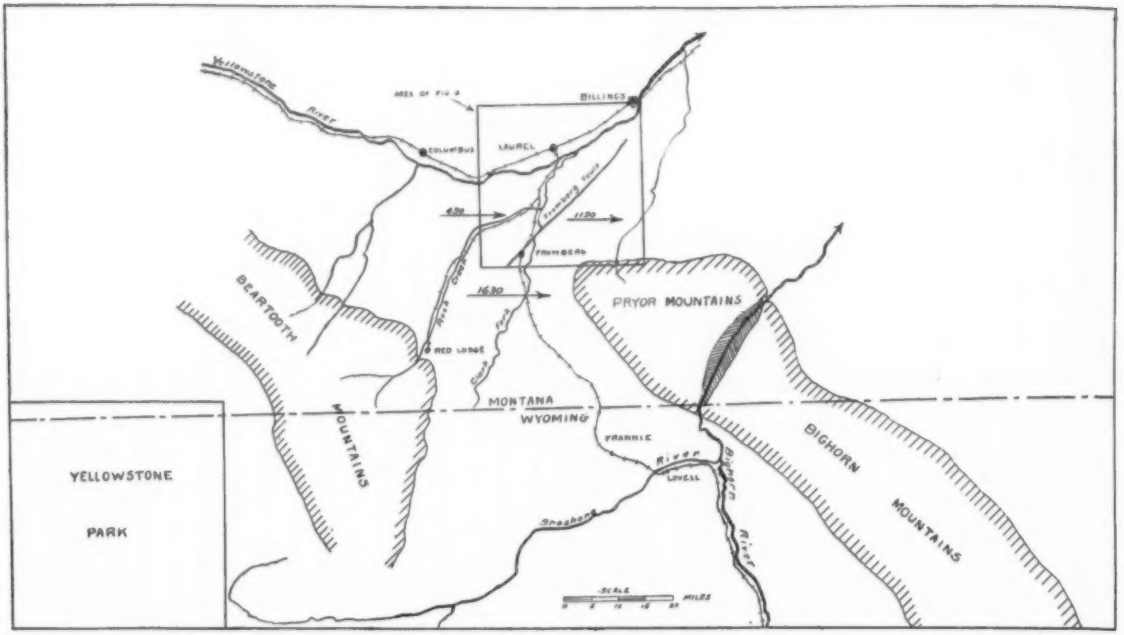
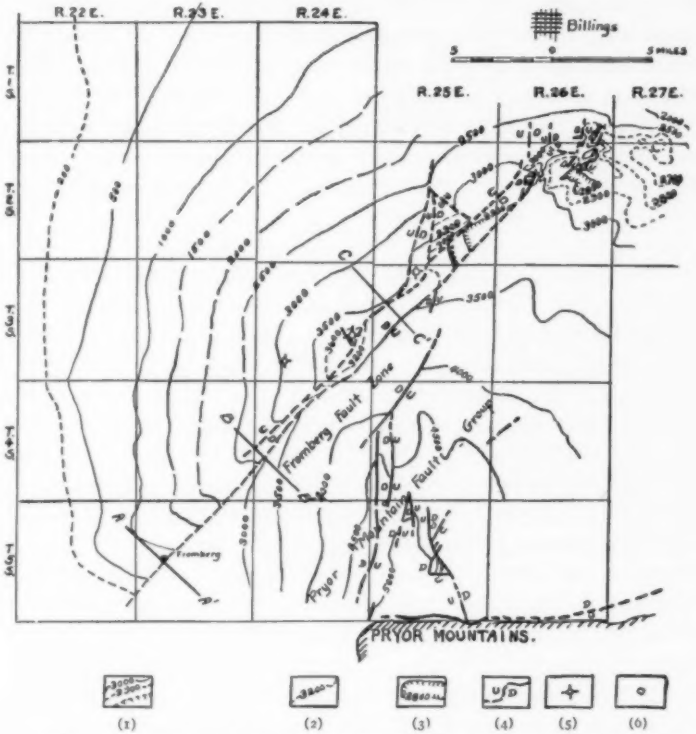


FIG. 1.—Index map of Billings region. Figures and arrows indicate the amount and direction of movement during mountain building.

reports now published.[1] It is evident from a comparison of the structural conditions, that the amount of crustal shortening involved



(1) Structure contours drawn on top of Cloverly formation Contour interval 500 feet except where intermediate contours are shown by special symbols. (2) Intermediate contour. (3) Depression contour. (4) Fault: U, *upthrow;* D, *downthrow.* (5) Dry hole. (6) Well being drilled.

FIG. 2.—Structural map showing folding and faulting in Billings region. After *Press Bulletin* U.S. Geological Survey, September 18, 1923.

in the upfolding of the Pryor and Bighorn Mountains is considerably greater than that required in the formation of the minor flexures

[1] E. T. Hancock, "The Geology and Oil and Gas Prospects of the Lake Basin Field, Montana," *U.S. Geological Survey Bull. 691-D* (1918); E. T. Hancock, "The Geology and Oil and Gas Prospects of the Huntley Field, Montana," *U.S. Geological Survey Bull. 711-G* (1920). W. T. Thom, Jr., "Oil and Gas Prospects in and near the Crow Indian Reservation, Montana," *U.S. Geological Survey Bull. 736-B* (1922).

immediately to the north. This variation in the amount of shortening implies a difference in the amount of horizontal movement west of the mountains as compared with the region northwest of them. These movements are indicated on the index map (Fig. 1) by arrows, which show the amount and direction of movement. The rotational strain developed most largely in the area included in Figure 2 (see Fig. 1) and needed to be adjusted there as well as in the source of thrusting. It is believed that some of the faults shown on the detailed map (Fig. 2) represent the local adjustment of this strain.

DESCRIPTION OF THE FAULTS

The faults with which this paper is concerned can be divided into two general groups, as may be seen on the map (Fig. 2). The Pryor Mountain fault group is associated with the Pryor Mountains. The other is a closely connected group some distance northwest and is called the Fromberg fault zone.

The Pryor Mountain group is composed largely of north-south trending faults. Notable exceptions are the east-west fault along the flank of the mountain uplift and the fault in the northwest corner of T. 4 S., R. 25 E. which has a trend of N. 40° E. Although none of the actual planes of faulting could be seen, the field relations suggested that all of these faults are of the normal or tensional type. Theoretical considerations, as developed later, indicate the probability that the long north-south fault in the central part of T. 5 S., R. 25 E. is an overthrust.

The Fromberg fault zone is composed of a long narrow fault block and several small branch faults. The general trend of the fault block is N. 40° E., but most of the faults branching from it have a north-south trend. The Fromberg fault is the outstanding feature of the Fromberg fault zone. This fault extends from a point several miles southwest of Fromberg for a distance of about 30 miles in a direction of N. 40° E. Near Fromberg it is a tensional or normal fault located on the southeast side of a slight syncline. Northeast of Fromberg, the fault is covered with alluvium in the Clark Fork Valley for a distance of about 9 miles. On the other side of this valley there is a fault in apparent continuation of the first one. In addition, there is a more pronounced syncline to the northwest which is bounded by a second fault parallel to the first

(Fig. 2, section *B–B'*). The displacement of this latter fault increases greatly to the northeast, and its distance from the first fault varies from less than a mile to more than a mile and a half. The strip between the two faults constitutes a downdropped block, or graben, which has a maximum depth of about 400 feet below the sides. As the displacement of the fault on the northwest increases until it equals that of the fault on the southeast, it causes an approximate neutralization of the displacement of the first fault as seen near Fromberg, so that a few miles northeast of *B–B'* (Fig. 2), the continuity of dip is unbroken except for the graben block. This equality of displacement of the two faults is maintained from that point to the end of the fault zone south of Billings.

The small faults associated with the graben are also of considerable interest. One important relation is the systematic arrangement of the up- and downthrow sides of the faults. The faults on the south side of the graben block all have the upthrow side on the east; those on the north have the upthrow side on the west. Although the character of the surface rocks was not suitable for exposing the fault planes under the existing topographic conditions, occasional drag effects and the relations of the nearest outcrops on opposite sides of the faults leave little doubt that all of the faults are of the normal or tensional type.

The lack of exposure of fault planes also prevented measurements of their dips. Along the graben, however, observations were made on outcrops on opposite sides of the faults and seemed to indicate that the dips of the faults bounding the graben block are approximately equal and measure about 60°. These estimated figures are used later in deriving the horizontal displacement which took place along the Fromberg fault zone.

THE MOUNTAIN-BUILDING FORCES OF THE REGION

There seems to be little room for doubt that the forces which caused the mountain building in the region were at least partly compressional, and that the shove came from the west. Evidence of compression may be found in the Heart Mountain and Beartooth Mountain faulting which Hewett[1] states may be contemporaneous

[1] D. F. Hewett, "The Heart Mountain Fault," *Journal of Geology*, Vol. XXVIII (1920), p. 537.

with the Lewis overthrust in northern Montana. In addition to these faults, Bevan[1] has described several cases of overturned beds which dip nearly 180° and may, therefore, be considered evidence of great thrusting. Thom[2] has pointed out, however, that there is considerable evidence that the folding in the Bighorn Mountains was accomplished by a combination of vertical and horizontal forces. According to his interpretation, a series of crests was started during the later Cretaceous by compressional forces acting from the Yellowstone Park region. One of these crests later became the Bighorn Mountains. Under this early arch, a decrease in load pressure made conditions favorable for the formation of an igneous magma. Later compressional forces acting on this magma as well as on the overlying rocks, caused the magma to rise and exert a hydrostatic pressure which acted largely in a vertical direction. The evidence to be presented later agrees with Thom's interpretation, which suggests a slight crustal shortening as a result of the mountain building.

THE FAULTING ACTION

The compressional forces which acted from the west during the building of the Bighorn and Pryor Mountains were much more effective in the mountain area than to the north as is shown by the arrows and figures on the index map (Fig. 1). The greater eastward movement along the arrow at the south resulted in a rotational strain in the region at the end of the mountains where the movements under compression were slight. The results of such a strain are indicated in the strain ellipsoid diagram (Fig. 3) which has been applied to the general region by R. T. Chamberlin.[3] This diagram shows that the axis of maximum elongation in this case would have had a northwest trend and that the resulting tension would cause faulting with a northeast trend. Such faults were formed in the region during the beginning of the mountain folding.

[1] Arthur Bevan, "Summary of the Geology of the Beartooth Mountains," *Journal of Geology*, Vol. XXXI (1923), pp. 457–59.

[2] W. T. Thom, Jr., "Structural Features of Central Montana," *Bull. A.A.P.G.*, Vol. VII (1923), pp. 5–7.

[3] R. T. Chamberlin, "A Peculiar Belt of Oblique Faulting," *Journal of Geology*, Vol. XXVII (1919), pp. 602–13.

The Fromberg fault (the longest member of the Fromberg fault zone) and the shorter parallel fault which cuts the northwest corner of T. 4 S., R. 25 E. are believed to be the only ones which resulted from the first strain. Later rotational strains, developed during further folding, caused tension along the Fromberg fault and the nearby shorter fault. These strains were relieved by movement in an east-west direction. The graben feature of the Fromberg fault zone and the slight syncline near Fromberg are believed to have been begun by this action. Horizontal displacement probably took place along the shorter fault and started the development of the north-south faults which are associated with it. These structural features were made more pronounced by further movements as the mountain building progressed. The graben is believed to have originated during the later movements which caused an incipient fissuring along the Fromberg fault. As the walls separated, the overhanging side yielded to the strain caused by its weight and dropped down to fill the space left.

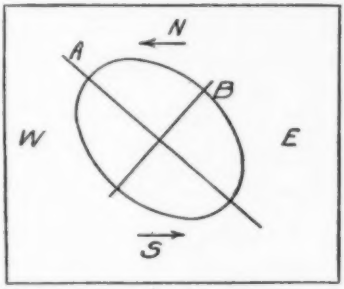


FIG. 3.—Strain ellipsoid for region of faulting. *A*, axis of elongation. *B*, axis of tension.

The change in the character of the faulting along the fault zone from Fromberg to section *CC'* (Fig. 2) might be explained in either of two ways. First, since the surface rocks showing the faulting are underlain by greater thicknesses of the soft Colorado shales near Fromberg than at section *CC'* (Fig. 2), it might be suggested that the graben structure continues as far as Fromberg, but is masked at the surface through the effects of shale flowage below. It is believed, however, that another explanation fits the observed conditions better. If the initial dip of the Fromberg fault plane had been greater near section *CC'* than at Fromberg, the effects of the later movements along the fault would have varied with the change in dip. It is postulated that this condition existed. At Fromberg where the dip was less, an eastward move-

ment on the east side of the fault was relieved by a slipping down of the overhanging side (on the west) with a very slight tendency to form a fissure along the plane of faulting. This tendency to leave an opening was relieved by shale flowage and caused the syncline to the northwest of the fault near Fromberg. The action is indicated in section *AA'* of Figures 4 and 5 which give the present structure and the relation of the horizontal and vertical components of motion on the fault plane. Farther northeast, as is shown in sections *BB'* and *CC'* (Figs. 4 and 5), the fissuring effect was much greater since the fault plane was more nearly vertical and the horizontal component of the motion dominated. This caused an increase in the size of the syncline shown in the Fromberg section which rapidly developed into the graben to the northeast as shown in sections *BB'* and *CC'* in Figures 4 and 5. These features can be seen plainly

FIG. 4

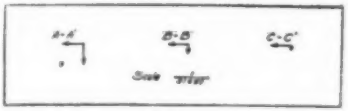


FIG. 5

FIG. 4.—Sketch structural sections along the graben. Letters refer to locations on Figure 2.

FIG. 5.—Components of motion along the graben. Letters refer to locations on Figure 2.

on the map (Fig. 2) where they are well shown by the structural contours.

Strong support is given to the second hypothesis as a result of an examination of the relation between the areal geology and the changes in structure along the Fromberg fault zone. If the graben feature extends the full length of the fault zone, but is disguised by flowage in the thicker overlying shales near Fromberg, the development of the graben effect should vary directly with the thickness of the shales. This condition does not exist, for the greater part of the development of the graben structure takes place between the lines *BB'* and *CC'* on Figure 2. This area is entirely within the outcrop of the Mowry shale. Therefore, the change in the character of the Fromberg fault is believed to be due to variation in the initial dip of the fault plane.

It is believed that the downdropped block of the graben was distinct as a structural unit during the last stages of the faulting action. At this time the mass southeast of the graben moved eastward relative to the downdropped block, and the block in turn moved east relative to the mass northwest of the graben. With this situation in mind it is an easy matter to explain the systematic arrangement of the up- and downthrow sides of the north-south faults connected with the graben. It is believed that the movement of the rock mass southeast of the graben was hindered somewhat by drag on the graben block, most particularly in the softer rocks near the surface. Since the thrust forces were applied largely

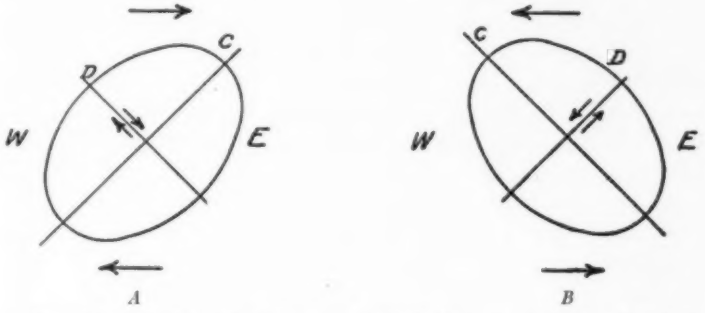


FIG. 6.—Strain ellipsoids in east-west vertical plane. *A*, northwest of graben. *B*, southeast of graben. *C*, axis of elongation. *D*, plane of fracture.

through the competent underlying rocks and the drag effects were greatest in the incompetent rocks above, a rotational strain was set up in an east-west vertical plane as shown in Figure 6*B*. From this diagram it is apparent that the forces which were active south of the graben were arranged so that they produced tension faults with a north-south strike, and with the downdropped side on the west.

To the northwest, the drag effects between the graben block and the adjacent rock mass caused an eastward motion in the incompetent overlying shales which was resisted by the competent rocks at depth. These forces gave rise to a rotational strain in an east-west vertical plane as shown in Figure 6*A*. This relation of forces

caused tension faults with a north-south strike which had the down-dropped side on the east. An inspection of the map (Fig. 2) shows that all of the north-south faults associated with the Fromberg fault zone follow the arrangement which should result from the mode of origin outlined above.

Contemporaneous with the faulting which relieved the rotational strain north of the Pryor Mountains, there was a tensional strain along the north front of the mountains which also resulted in faulting. Although there was considerable compression on the east and west sides of the Pryor Mountains, this effect was notably on the north flank. The bodily uplift under the conditions described by Thom[1] caused considerable tension on the northern flank of the mountain anticline and resulted in faulting. The first break is believed to have had an angular course which is now shown by the north-south fault in the central part of T. 5 S., R. 25 E., and the fault along the mountain flank from the point of junction eastward. It is believed that for a considerable portion of the uplift which followed the faulting along the mountains, the rock mass west of the north-south member of the fault acted as a unit with the adjacent uplifted rocks, and was elevated to a greater altitude than it now possesses. Likewise this part was moved eastward by the action of the compressive forces so that the north-south fault was a plane of overthrusting for a time. Field evidence, however, failed to show this relation.

In a late stage of the mountain-building, the tension developed west of the north-south fault in the central part of T. 5. S., R. 25 E., was too great for the strength of the rock materials there and caused faulting which extended the pre-existing fault along the mountain flank. The displacement along the new fault was considerable at the point of junction with the north-south fault, but diminished rapidly to the west so that it is of doubtful effect 3 or 4 miles away. The original tilting of the block which is bounded on the east by the north-south fault under discussion and on the south by the later fault along the mountains, combined with the later adjustment which allowed the east side of the block to drop more than the west, set up torsional strains to the north. These strains were relieved by the distributed faults shown on the map (Fig. 2) in T. 5 S., R. 25 E.

[1] W. T. Thom, Jr., *loc. cit.*

THE EXTENT OF ADJUSTMENT

In order to gain a quantitative idea of the completeness of adjustment of the rotational strains produced by differential movement at the end of the Pryor-Bighorn Mountain group, it is necessary to measure the effects of the various folding and faulting actions which are involved, and to take their algebraic sum. The crustal shortening due to folding in the Pryor Mountains and in the area north of them, and the horizontal displacement along the faults which adjusted the rotational strain, can be estimated only in a general way, but it is believed that such results are of sufficient value to be considered.

The principal difficulty in making an estimate of the amount of crustal shortening involved in the folding of the Pryor Mountains is the lack of detail in the structural data available. The general facts are known and are followed as closely as possible in the estimate. In computing the length of the Cloverly formation over the fold, certain dips were assumed to have persisted for considerable distances. This assumption introduces a possibility of underestimating the shortening, for if the dip is undulatory, the slope length required for any given increase of altitude within a certain distance is greater than if the dip is regular. On the other hand, the somewhat bodily uplift of the Pryor Mountains could have caused a considerable amount of stretch in the beds on the steeply dipping sides of the anticline, so that an overestimate of the shortening might result from that cause. Errors of these sorts would neutralize each other to a considerable extent.

In computing the shortening due to folding in the mountains, the amount of uplift for each average dip was the principal assumption. By use of the angle of dip and the vertical height, the length of the slope was computed by dividing the amount of rise by the sine of the angle. The product of the slope length and the cosine of the angle gave the horizontal length. The amount of shortening was obtained by subtracting the horizontal length from the slope length. The results are shown in Table I. Figure 7 shows a structural profile constructed according to this data.

In a similar manner a rough estimate can be made of the shortening involved in the more gentle folding just north of the Pryor

Mountains. In this case a rise of 5,100 feet at a uniform dip of 6° was assumed, with a descent to the east at an equal rate. Observation indicates that the general dip to the east is not so steep. The overestimate of shortening caused by such an error would probably be just about compensated by the effects of minor irregularities in the dip. The folding north of the mountains was found to have caused a shortening of about 450 feet according to these figures.

In adding up the effects of the structural disturbances in the region, a positive sign was used for shortening due to folding in the mountains. A negative sign was taken for shortening and horizontal movements in adjustment of rotational strain in the region north of the mountains. Following this plan, we find that $+1{,}629-450=+1{,}179$ feet. Since this figure represents the

TABLE I

Section	Dip	Rise (Feet)	Slope Length (Feet)	Horizontal Length (Feet)	Shortening (Feet)
A	6	7,000	66,972	66,600	372
B	15	3,000	11,685	11,194	491
C	6	500	4,783	4,757	26
D	6	500	4,783	4,757	26
E	18	2,400	7,766	7,386	380
F	30	500	1,000	856	144
G	5	7,100	81,460	81,270	190
Total shortening					1,629

difference in shortening due to folding, it also must be the amount of differential movement which produced the rotational strain at the north of the mountains.

It is now desirable to determine to what extent the differential movement, estimated above, was compensated by horizontal movement along the faults in the region between the Pryor Mountains and the Yellowstone River. The dip of the fault planes of the two sides of the graben block as given previously is 60°. This is assumed to be the true dip and to continue to considerable depth. In that case a horizontal separation of 462 feet in a plane at right angles to the length of the graben zone is required to allow the central block to drop 400 feet. Further, the hypothesis of origin states that the separation of the graben was accomplished by an eastward movement of one of the structural units of the region.

Horizontal displacement of 670 feet in this direction is needed to explain the faults.

The faults of the Pryor group which are located along the range line east of R. 24 E. and across the northwest corner of T. 4 S., R. 25 E., are the only other ones which are believed to have made a noteworthy adjustment of the rotational strain at the end of the line of mountain folding. Along these faults, which are believed to be closely related in origin, there is a vertical displacement of about 100 feet. Here, too, the field conditions did not permit a measurement of the dip of the fault planes. If the dip is assumed to be the same as in the case of the sides of the graben, then the horizontal movement along these planes in an east-west direction needed to explain the displacement is 78 feet.

The adjustment by faulting as estimated amounts to about 750 feet. By applying the rule stated before we find that the differential movement, +1,180 feet − 750 feet = +430 feet. Thus we see that there is 430 feet of differential movement not compensated by any structural feature considered, but that much the greater part of the differential movement was adjusted in the immediate neighborhood of the end of the mountain folding.

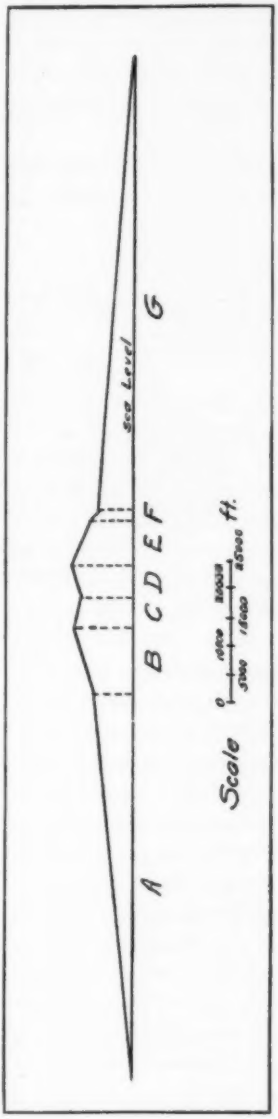


FIG. 7.—Profile constructed for data in Table I

NOTE ON A COBBLE OF PECULIAR SHAPE[1]

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ABSTRACT

A cobble of symmetrical lenticuloid form bearing a number of very distinct residual facets was taken from a pothole in which it had acquired its characteristic shape. The circumstances of its origin and accompanying types of abrasive motion are analyzed and conclusions drawn as to their relative importance and the relative rates of abrasion of the cobble and of the pothole.

In the study of physical geology it is apparent that the most important results in point of quantity are achieved by a relatively small number of so-called typical processes. From a detailed examination of any particular group of these processes it is equally apparent that a number of quantitatively subordinate processes under very special conditions of climate, locality, or rock produce results which are either of very distinctive character or which perhaps simulate closely the results of one of the more widespread major processes. The investigator who is examining critically the data of geologic history must ever keep in mind these special processes as well as those of more general occurrence in order that he may neither be baffled by a strange feature nor led astray by one which closely resembles another of more common development.

The following description of an unusual cobble-shaping process is presented as a contribution to the subject of cobble shapes which may prove suggestive in future interpretation. The cobble shown in Figure 1 was found in a pothole on the Virginia side of the Potomac River several miles below Great Falls. Its peculiar shape at once commanded attention and is described below. The pothole in which it was found is at the end of a ledge of crystalline rock which extends some distance into the river channel and is covered by several feet of water during flood, but is dry during most of the year. Unfortunately no photographs nor measurements were made

[1] Published by permission of the director of the United States Geological Survey.

of the pothole, but it may be described briefly as a rather shallow pothole of spherical form of which the abraded portion was about a foot in diameter and 3 or 4 inches deep. The total depth of the concavity was somewhat greater, the pothole occupying the central part only.

The cobble, which is composed of dark-green amphibole schist, has an elongated ovoid form, 17 cm. in length, 8 cm. in width, and 7 cm. in thickness. (See Fig. 1.) Its longitudinal profile is notable for the nearly sharp ends and the long uniform side curves, making a lenticular profile with slightly rounded corners. The transverse profile is roughly trapezoidal with nearly equal base angles of about

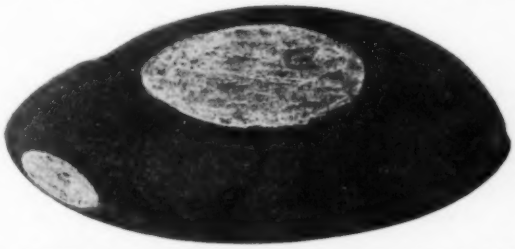

FIG. 1.—Photograph of cobble of peculiar shape. Facets *c* (at left) and *d* (at right) were coated with chalk to photograph more distinctly.

80° and rounded corners. (See Fig. 2.) Near the centers of three of the four sides of the trapezoidal lens are facets, and near one end of the fourth side is a similar facet. Neither the facets nor the major axis of the cobble seem due in any essential way to the planes of schistosity.

The greater part of the surface of the cobble is smooth and freshly abraded to the curvature of a dominant lenticuloid form. The two end points are battered and somewhat less smooth. The surfaces of the facets are darker in color, slightly oxidized, and less smooth than the surface of the principal lenticuloid surface. At two or three places on the surface of the cobble, small fragments are broken out along the planes of schistosity.

In general form, in the smoothness of its surface, and in the battered character of the ends, the cobble suggests a stone implement of the hammerstone form and might easily be taken for such had it

not been found under conditions which indicate a natural rather than artificial origin.

The facets are clearly the surviving remnants of an older surface. The dominant curvature of the cobble is somewhat greater than the average internal curvature of the pothole, but is believed to have been controlled by the latter since abrasion by rolling and knocking proceeds very much more slowly between two surfaces as they approach to the same curvature, one convex and the other concave. The original joint fragment, somewhat smoothed but otherwise little modified by abrasion, was probably dropped into the pothole

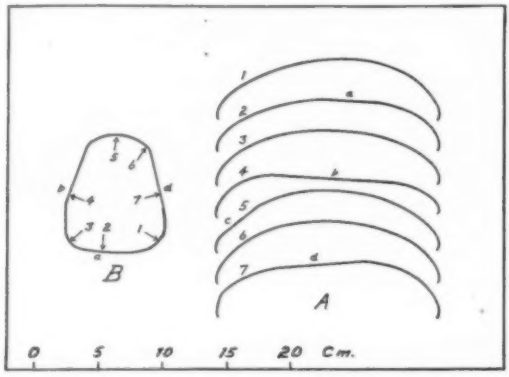

FIG. 2.—Profiles of cobble. *A* shows a series of longitudinal semi-profiles 1 to 7, and the facets *a*, *b*, *c*, and *d*. *B* shows the transverse profile and the orientation of each of the seven longitudinal profiles shown in *A*.

in the course of an exceptionally violent flood or perhaps from floating ice. At that time it had nearly the same maximum dimensions as at present, as is shown by the preservation of facets on three sides and near one end. Such a block having thickness and width nearly equal, and length more than twice as great, would tend under the impetus of water passing over the pothole to roll about its longer axis and would be relatively unstable. Corners would be quickly reduced until the new lenticuloid form had developed over considerable areas. Exceptionally, the cobble might be turned end over end by stronger currents, and the rounding of the ends to smooth

conformability with the principal lenticuloid form indicates that this has taken place. The roughened, battered character of the ends indicates that this action, as would be expected, has been more violent than the more normal turning about the long axis. The removal of the material at the ends and the increasing instability of the cobble would seem to tend toward a rocking motion favoring the development of a profile of somewhat greater curvature than that of the pothole, though controlled by it as suggested above. As the development of this more curved profile proceeded and the facet remnants became reduced in area, there would be a tendency to combine with the rolling about the long axis a spinning about any of the shorter axes normal to it which might be momentarily vertical. This latter motion would supplement the former and produce similar abrasion.

The question may properly be asked whether the pothole was not formed by the cobble and is therefore of the same age. This seems highly improbable. The rock of the pothole is believed to be much more resistant to abrasion than that of the cobble, though no tests were made. Abrasion of a pothole is removal of rock from a concave surface, that of a cobble removal from a convex surface. The latter process is inherently much more effective. The total abraded area of the pothole is roughly estimated at 900 square centimeters, that of the cobble at 300. The amount of material removed from the cobble during abrasion to its present form in the pothole is estimated at not over 400 cubic centimeters.

If the pothole rock be twice as durable as the cobble rock and if the concave surface of the pothole be, by virtue of its form, four times as resistant to abrasion as the convex surface of the cobble under the conditions obtaining in the present instance, then the pothole would have lost through the work of this particular cobble only one-eighth of what actually has been removed, or 50 cubic centimeters of material. The effect of weathering during much of the year when the abrasion is not active has been ignored but it is believed that it would affect the cobble at least as severely as the pothole. The ratio of eight to one between cobble loss and pothole loss seems conservative to the writer but will suffice for the discussion in hand. The 50 c.cm. were removed from an area of 900

square centimeters and represent an average thickness of one-eighteenth of a centimeter, or a little over one-half millimeter. It seems probable, therefore, that in the abrasion of the pothole at least some scores of cobbles were abraded to a similar extent, but not necessarily in a manner similar to that of the cobble described.

From the description and discussion above the following conclusions seem justified.

1. The facets on the cobble are older than the rest of the surface, a condition which is contrary to that of several more common types of facetted cobbles.

2. The lenticuloid shape of the cobble has been controlled by the curvature of the pothole, though the curvatures of the two are not identical.

3. There have been four principal components of motion, together with the various combinations of these, as follows: (*a*) rolling about the long axis; (*b*) (1) rocking about a horizontal short axis, (2) complete overturning about a horizontal short axis with end bumping; (*c*) spinning about a vertical short axis.

Of these motions, *a* was probably dominant at first with *b* (1) and *c* coming to be of importance in latter stages. *b* (2) has been of sporadic occurrence during the whole history under exceptionally violent flood conditions.

4. The pothole had already been abraded to essentially its present form when the cobble here described was introduced, and represents the abrasion of some scores of cobbles of similar size and hardness.

STUDIES FOR STUDENTS

THE TEACHING OF CRYSTALLOGRAPHY

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ABSTRACT

For the use of beginning students in mineralogy or crystallography, simplified directions are given for applying the Goldschmidt method to the study of crystals on the two-circle contact goniometer. The methods for plotting face-poles in the gnomonic projection, determining symbols of faces from their face-pole co-ordinates, transfeirrng Goldschmidt to Miller symbols and vice versa, determining axial ratio, and crystal drawing are all presented.

In teaching crystallography the use of some sort of a projection is desirable, as it brings out the true symmetry of the crystal (i.e., the angular relations between the faces) and masks the irregularities due to the conditions of growth. The relative sizes and shapes of faces, or their distances from the center, are of no importance in determining symmetry; in fact, if these features were what conditioned the symmetry, probably no crystal could be called a symmetrical solid. Moreover, a projection often indicates the faces demanded by symmetry, should some of them be missing on the crystal.

The gnomonic projection is now recognized by many crystallographers as the type of projection most adapted to their use. Until recently, the detailed description of this projection was not available in English. Even now, the writer knows of no description of crystallographic methods based on this projection which the average college undergraduate can readily absorb in the few weeks given to this branch of study in most mineralogy courses.

Accordingly, the following set of laboratory directions has been prepared. It is used in a six-month course in mineralogy (for Juniors and Seniors who have had no previous mineralogy), about five weeks of which are devoted to the whole subject of crystallography. These directions are used as a guide for laboratory work on the two-circle contact goniometer, and as written apply especially to the

orthorhombic system. In this course, the study begins with the asymmetric class of the triclinic system and proceeds in order of increasing symmetry to the normal class of the isometric system. The detailed study of triclinic and monoclinic crystals by means of the Goldschmidt method is not given in this first course. These two systems are covered in a broad way by studying the seven type forms of the normal class of each system, and by determining the symmetry and class of crystals and models in the laboratory. Also the crystal axes are selected, the general forms named, and the prominent characteristics noted.

In studying the orthorhombic system, an explanation of the gnomonic projection is given, together with the methods of plotting faces on this projection by means of the φ and ρ angles obtained by measurement of crystals on the two-circle contact goniometer in the laboratory. The seven type forms of the normal class of this system are developed during the lecture period, using the gnomonic projection. Part of the laboratory work on the orthorhombic system consists in the measurement on the two-circle contact goniometer of one or two rather simple crystals, the preparation of a gnomonic projection for each crystal, and the calculation of axial ratio, determination of indices of all faces (after selecting the unit face or faces), and drawing of the crystal from the projection, according to the accompanying directions.

The method of study of the remaining three systems is analogous to that in the orthorhombic system. The only important modifications necessary to make the laboratory directions suitable for these latter systems are in respect to the determination of the axial ratio, the nomenclature of the crystal axes, and the determination of the Goldschmidt and Miller indices in the hexagonal system. These changes are indicated by short footnotes in the laboratory directions which can easily be amplified in the classroom. It is considered advisable in this first course to give only the G_1 position in the hexagonal system, where the co-ordinate axes from which the Goldschmidt symbols are obtained do not coincide with the crystal axes, but bisect them. Moreover, the terms p_0 and q_0 are not introduced, though $p_0 = \frac{x_1}{r}$, and $q_0 = \frac{y_1}{r}$; thus they may be easily obtained if it seems desirable.

While these directions are written for the two-circle contact goniometer, they can be used by beginning students on the two-circle reflection goniometer if it is remembered that on the reflection goniometer the crystal is mounted, so that the *c*-axis is horizontal (see paragraph 4), and paragraphs 7 and 8 are modified slightly (i.e., φ readings are obtained in the manner described, but from the vertical circle readings, and ρ readings are obtained from the horizontal circle readings, the zero-point being the reading obtained from the (001) face).

The whole idea in preparing these directions was to gain simplicity. Everything stated is not true for all cases, and simple prismatic crystals are needed for beginning work. As the student becomes accustomed to the method as applied under these conditions, he can readily go on to other types of work, by consulting certain references.[1] In short, these directions merely outline the various operations. The student is enabled to see how well this method works out in the study of crystals. For the reasons behind the various statements made, the references must be consulted.

TWO-CIRCLE CONTACT GONIOMETER EXERCISE

DIRECTIONS

(NOTE.—These directions apply specifically to the orthorhombic system, but with slight changes are applicable to other systems.)

1. Make two free-hand sketches of the crystal, one a top view, and one a side view. In each of these sketches, show all the faces of the crystal as they would appear if the crystal were a cardboard model which could be unfolded along its edges so that all the faces would lie in the plane of the paper.
2. Number the faces (in any order), but be sure to give the same faces in each sketch the same number. Any identifying marks that are seen on the crystal faces should appear in the sketches.
3. From preliminary examination determine the apparent symmetry of the crystal and so obtain the probable crystal system; tentatively select the crystallographic axes.
4. Mount the crystal on the Goldschmidt two-circle contact goniometer with the *c*-axis vertical and directly above the center of the pin bearing the

[1] *American Mineralogist*, Vol. V (1920). Series of articles on the Goldschmidt two-circle method. These have been reprinted and combined into a single pamphlet, which was used constantly in the preparation of these directions. Dana-Ford, *Textbook of Mineralogy*, 3d ed., 1922. Walker, *Crystallography*, 1914. Goldschmidt, *Index der Krystallformen der Mineralien*, Vol. I, Berlin, 1886.

platform or table *t* (Fig. 1). Set the pin on which the crystal is mounted (in wax) in its hole and tighten the screw *s* with the key, having the four holes *h* in the support *b* in alignment with the dominant vertical faces of the crystal. Loosen the large screw *S* (hidden by a leg in Fig. 1) at the base of the instrument, so that the ball and socket joint carrying *b* rotates easily. Orient the vertical faces of the crystal parallel to the plate *P* on the steel rod *R* when the angle on the vertical circle *V* reads 90° and the plate is in a vertical position. In doing this, have the four holes *h* parallel to, or normal to, the vertical circle *V*. This orientation is accomplished by means of the key, which is inserted in the holes *h*. When oriented, tighten the screw *S* at the base of the instrument, thus clamping the ball and socket joint. The crystal may now be considered to lie in the center of a sphere, of which the vertical circle *V* corresponds to a meridian and the horizontal circle *H* to the equator. The vertical axis of the crystal then points toward the north pole (at 0° on *V*) and the plane of the gnomonic projection is perpendicular to the vertical axis and tangent to the sphere at 0° on *V*. As the plate *P* is brought parallel to a crystal face, the rod *R* represents a normal to the face, and where the prolongation of the rod cuts the plane of the gnomonic projection lies the point in the projection representing the face in question.

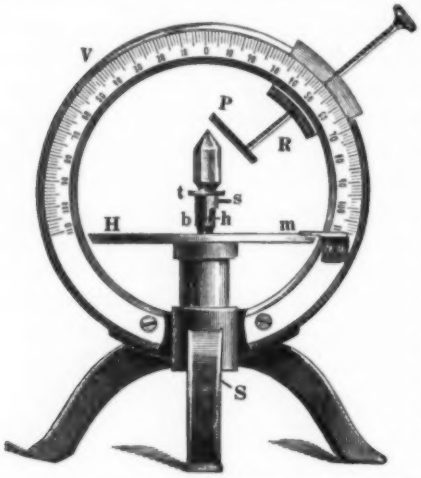

FIG. 1.—The Goldschmidt two-circle contact goniometer.

5. Prepare a table as follows:

Number	Symbol	Letter	Horizontal Reading	Vertical Reading	φ	ρ

6. Measure successively the *position angles* of the normals to the various faces: (1) in the prismatic zone, (2) in the other zones. These readings give the

positions of the normals (represented by the steel rod *R*) to the various crystal faces with reference to a horizontal and a vertical plane (represented by the two circles). The plate *P* carried on the steel rod should not touch the crystal, but should be close to it, so that by sighting the trace of the crystal face is seen to be parallel to the plate. A sheet of paper held as a background may aid in this operation. The plate should lie in the plane of the vertical circle when taking readings on the vertical circle, and normal to this plane for readings on the horizontal circle. Take the readings on plane faces to tenths of a degree (by estimate), and enter them in the table, being sure the proper number for each face is set opposite the readings for that face. If the crystal is disturbed while these readings are being made, errors will result; and the measurement will have to be repeated.

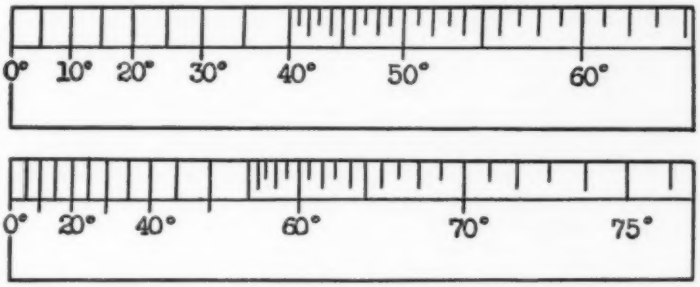

FIG. 2.—Scales giving *d* for plotting ρ angles in gnomonic projections with 5- and 2½-cm. radius fundamental circles.

7. Make a gnomonic projection of the crystal by plotting the normal points (called *face-poles*), using a protractor to plot the angles listed under the horizontal reading column. Where a line parallel the ends of the paper passing through the center of the fundamental circle of the gnomonic projection cuts the right side of the circle is the zero-point for horizontal circle readings. These readings are measured clockwise from this point, and may be anything up to 360°. After the lines showing the directions to the desired face-poles have been plotted from the angles given in the horizontal reading column, the distance *d* (Fig. 3) of the respective face-poles from the center of the projection is laid off by means of a scale giving the values of d^1 for various angles listed in the vertical reading column. Scales are shown in Figure 2 for fundamental circles of 5- and 2½-cm. radius. Use the larger circle unless some of the angles in the vertical reading column are between 60° and 90°.
8. In this gnomonic projection determine the true symmetry of the crystal; thus check the previous selection of system and crystal axes. Draw the

[1] For values of *d* in a 5-cm. radius fundamental circle, see *American Mineralogist*, Vol. V (1920), p. 119.

directions of the *a*- and *b*-axes (revised from the previous conception if necessary) in the gnomonic projection and rotate the paper, so that the *b*-axis extends from left to right. Where the plus (right) side of the *b*-axis cuts the fundamental circle is the corrected zero-point for all horizontal circle readings. In the foregoing table add to (or subtract from) each reading under the horizontal circle column the angular difference between the directions of the corrected zero-point for horizontal circle readings and the zero-point originally used (see paragraph 7), and enter these new values under the φ column in the proper places. In general the vertical circle readings may be directly transferred to the ρ column with no changes, unless the faces on both ends of the crystal were measured, in which case the ρ readings for the faces on what is taken as the lower end of the crystal equal 180° minus the vertical circle readings obtained.

9. Select some prominent face which cuts all three crystallographic axes (i.e., a pyramidal face) as the unit face, with Miller indices (111). If there is no such face, choose as unit faces two faces which are prominent and each of which cuts two axes and is parallel to the third, the two faces cutting all three axes; i.e., these faces will have Miller indices (110), (101), or (011). In case no pyramidal unit face is available, the location of the face-pole of such a face is easily obtained in the gnomonic projection from the locations of the face-poles of the known unit faces by drawing lines through the face-poles of these parallel the *a*- and *b*-axes and the point where these meet or where one of them meets the line showing the direction of the unit prism (110) is the location of the face-pole of (111). Measure (in cm.) the co-ordinates (x_1, y_1) of the face-pole of the unit face (111) in directions parallel the *a*- and *b*-axes respectively (Fig. 3).[1]

10. Now determine the Goldschmidt (Gdt.) symbols (p, q) of the other faces represented in the projection by dividing their face-pole co-ordinates, x ($=px_1$) and y ($=qy_1$) measured in cm. in directions parallel the *a*- and *b*-axes respectively, by the co-ordinates of the face-pole of the unit face (x_1, y_1). Convert these symbols (p, q) into Miller indices (*hkl*, see below) and enter them along with the corresponding letters in their proper places in the table (paragraph 5). Note the *rationality of indices*, or the validity of Hauy's law. The letter corresponding to each crystal form may be found in Goldschmidt's *Krystallographische Winkeltabellen* by looking up the crystal being studied. In this book the φ and ρ angles for the various faces are also given, and these values may be compared with those obtained by the student.

Figure 3 is a gnomonic projection showing a few face-poles for topaz, an orthorhombic mineral. The unit face *o* (111) has co-ordinates x_1, y_1

[1] The unit face in the tetragonal system will be either (111) or (101), depending on whether the face chosen cuts all three axes, or is parallel one of the *a*-axes. In the hexagonal system the unit face may be either (1011) or (11$\bar{2}$1), depending on the same conditions. In determining x_1 and y_1 (and x and y, see paragraph 10) in the hexagonal system, the distances are measured in cm. along the two co-ordinate axes that bisect the angles between the a_1 and a_2 and the a_2 and a_3 crystal axes, respectively.

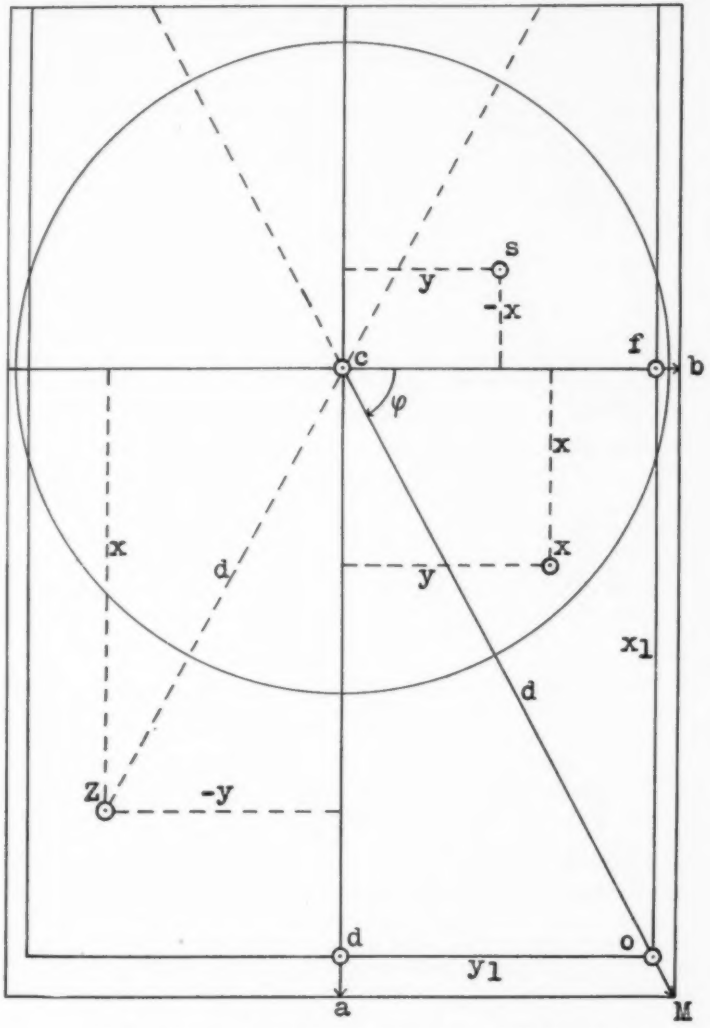

FIG. 3.—Gnomonic projection of a few faces on a topaz crystal

which respectively $=9.0$ and 4.8 cm. (assuming $r=5$ cm.). For this unit face, $\varphi=62°$ and $\rho=64°$ (whence $d=10.2$ cm. where $r=5$ cm.). Note that the face-pole of (111) lies on the shaft of the arrow representing M (110) and that zonal lines drawn through the face-pole of (111) parallel the a- and b-axes, cut these axes at the face-poles of f (011) and d (101) respectively. The face-pole x (123) has co-ordinates $x=3.0$ cm. and $y=3.2$ cm., whence p, $q=\frac{1}{3}, \frac{2}{3}$. s, the face-pole of (136), has co-ordinates x, $y=-1.5$ and 2.4 cm. respectively, whence p, $q=-\frac{1}{6}, \frac{1}{3}$. Face $(3\bar{3}4)$ with pole Z has co-ordinates x, $y=6.8$ and -3.6 cm. respectively; thus p, $q=\frac{3}{4}, -\frac{3}{4}$. d for this face $=7.7$ cm. Faces shown by poles a, b, and c have for their Gdt. symbols (p, q) ∞o, $o\infty$, and ∞, respectively.

11. The conversion of the Gdt. symbols into Miller indices is not difficult. Any face is described by two Gdt. symbols, but has three Miller indices. The two Gdt. symbols correspond to the first two Miller indices. The third Miller index is always obtained by adding unity. Thus to convert Gdt. symbols to Miller indices, add unity for the third place, and clear of fractions. A few examples will make this conversion clear.

Gdt.		Adding Unity in the Third Place			Miller		
$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	1	1	2	3
1	1	1	1	1	1	1	1
o	$\frac{1}{2}$	o	$\frac{1}{2}$	1	o	1	2
$\frac{1}{2}$	o	$\frac{1}{2}$	o	1	1	o	2
o	2	o	2	1	o	2	1
2	o	2	o	1	2	o	1

Gdt.		Adding Unity in the Third Place			Miller		
o	1	o	1	1	o	1	1
1	o	1	o	1	1	o	1
o	o	o	o	1	o	o	1
o	4	o	4	1	o	4	1
$\frac{3}{4}$	o	$\frac{3}{4}$	o	1	3	o	2
$\frac{3}{4}$	$\frac{1}{4}$	$\frac{3}{4}$	$\frac{1}{4}$	1	9	4	6

Wherever both Gdt. symbols are the same, but one is written. Thus the face with Miller indices (111) has (1) for its Gdt. symbol and the face (001) has (o) for its Gdt. symbol. This is *not* shown in the foregoing table.

If a face is parallel to the c-axis, its face-pole is represented in the gnomonic projection by an arrow. In short, both of its Gdt. symbols will contain the term ∞ (infinity), although in practice only one of the ∞ symbols is ever used, the other being understood. In this case the Gdt. symbol given will locate a point which (in connection with the co-ordinate center) fixes the direction of the arrow. Any face parallel to the c-axis has ∞ in its Gdt. symbol, and no face that is not parallel to the c-axis has ∞ in its Gdt. symbol. Moreover, of the two ∞ signs always understood in the Gdt. symbol of any face parallel to the c-axis, the coefficient of one of these ∞ signs is always given as unity and the ∞ sign of the other coefficient is dropped. Thus if one of the coefficients is not originally obtained as unity, multiply both coefficients by some quantity that will change the value of the *smaller* coefficient, to unity. Then to convert Gdt. symbols containing ∞ to Miller indices, add unity for the third place (as was done in the cases given above),

and clear of fractions. To clear of fractions, each term is divided through by ∞. A few illustrations will make this whole process clear.

Symbols Obtained from Gnomonic Projection	Gdt. Symbols	Adding Unity in the Third Place	Clearing of Fractions by Dividing Through by ∞	Miller Indices
3∞ 2∞	$\frac{3}{2}$ ∞	$\frac{3}{2}\infty : 1\infty : 1$	$\frac{3}{2}$ 1 0	3 2 0
∞ 4∞	∞ 4	$1\infty : 4\infty : 1$	1 4 0	1 4 0
∞ 0	∞ 0	$1\infty : 0 : 1$	1 0 0	1 0 0
0 ∞	0 ∞	$0 : 1\infty : 1$	0 1 0	0 1 0
∞ ∞	∞	$1\infty : 1\infty : 1$	1 1 0	1 1 0
∞ 2∞	∞ 2	$1\infty : 2\infty : 1$	1 2 0	1 2 0
$\frac{3}{2}\infty$ $\frac{1}{2}\infty$	$\frac{3}{2}$ ∞	$\frac{3}{2}\infty : 1\infty : 1$	$\frac{3}{2}$ 1 0	4 3 0

All the faces given in the foregoing table are parallel to the c-axis, and are represented by arrows in the gnomonic projection. The direction of each of these arrows is determined by passing a line through the center of the co-ordinate system and through a face-pole with (in the foregoing order) the Gdt. symbol (32), (14), (10), (01), (11), (12), $(\frac{3}{2}, \frac{1}{2})$.[1]

12. For converting Miller indices to Gdt. symbols proceed in reverse order to that given above. That is, multiply each term of the Miller indices by some quantity such that it makes the third Miller index unity, and then drop this index. In case the third Miller index is zero, multiply each of the other two terms of the Miller indices by ∞, and drop the third index. It may then be necessary to multiply the coefficients of the two ∞ signs obtained by some quantity such that the smaller coefficient is made unity (also drop the sign of the other coefficient) in order to obtain the correct Gdt. symbol.

13. Determine the axial ratio ($a:b:c$) for the crystal, by using the following formulas:

$$a=\frac{y_1}{x_1}; \qquad c=\frac{y_1}{r}$$

where r = the radius of the fundamental circle, generally taken as 5 cm. (Of course, b in the axial ratio = 1.)[2]

[1] To get the Bravais-Miller symbols of the hexagonal system from the Gdt. symbols, add 1 in the fourth place. In the third place, add a number or fraction such that the numerical sum of the first three Bravais-Miller indices equals zero. It may then be necessary to clear of fractions as before.

[2] These formulas hold only in the orthorhombic system; but similar calculations may be made in the other systems. Thus in the tetragonal system, the second of the foregoing two formulas is all that is needed. In the hexagonal system $c=\frac{.866x_1}{r}$. In the tetragonal and hexagonal systems $x_1=y_1$. If 1011 is chosen as the unit face in the hexagonal system, since the pole of this face lies on a co-ordinate axis, y_1 will apparently equal zero. But in all calculations y_1 should be considered $=x_1$. In short, 1011 in the hexagonal system is analogous to 101 in the tetragonal system. In the isometric system $x_1=y_1=r$.

14. Draw a border to the projection, making its 4 sides parallel the *a*- and *b*-axes, and its 4 corners coincide with the direction-arrows of the unit prism.
15. Draw zonal lines through the various face-poles, making the necessary compensations to give equal distances (like units) in parallel directions. In the gnomonic projection all the face-poles lying on any straight line represent faces in a single zone. Enter the indices of the various faces near their poles in the gnomonic projection.
16. From the projection make two drawings of the crystal: top view or plan (orthographic), and side view (parallel-perspective or clinographic). See following directions.

CRYSTAL DRAWING FROM THE GNOMONIC PROJECTION

By using a needle, transfer the revised gnomonic projection (paragraph 8) to a large rectangular sheet of paper, putting it on the left side of the paper with the center point of the gnomonic projection slightly above the horizontal center line of the large sheet of paper, and in such position that the *b*-axis (when the sheet of paper is held in a vertical position) is inclined (downward to the right) 20° to the horizontal (Fig. 4*A*). In drawing the crystal, two triangles (or a triangle and a straight edge) will be found to be very convenient.

ORTHOGRAPHIC DRAWING OR PLAN

1. Make this in the upper right-hand part of the large sheet of paper. This is easily made, as the direction of the edge between any two crystal faces in the orthographic projection is perpendicular to the line connecting the two face-poles concerned in the gnomonic projection.
2. In the case of an edge between a face represented in the gnomonic projection by an arrow (i.e., a prismatic face) and a terminating face, its direction in the orthographic projection is obtained by taking a line normal to the line in the gnomonic projection which is terminated by an arrow and thus represents the prismatic face in question; i.e., in this case the terminating face on the crystal is of no importance; the direction of the arrow controls the whole thing.
3. In preparing the orthographic drawing, it is convenient to draw the prismatic outline first. Thus in drawing the crystal of topaz (Fig. 4*B*), the edges between faces 1–9, 2–10, 3–11, and 4–12 were drawn first, and resulted in a rhombus. The directions of the sides of the rhombus were obtained by successively placing a straight edge (or one side of a triangle) along the directions of the arrows to face-poles 1, 2, 3, and 4 in the gnomonic projection, laying one side of a right-angled triangle along this straight edge, and drawing lines along the other side (not the hypotenuse) of the triangle.

4. In drawing a crystal, an idealized product is generally wanted. Thus care must be taken to preserve every equality of dimensions demanded by the symmetry. For this reason, the topaz crystal has the cross-section of a rhombus; not a rhomboid. The length of a side of the rhombus was arbitrarily chosen to give a drawing of convenient size.
5. Next the corners of the rhombus were truncated by the two pinacoids (faces 5–6 and 7–8), making them of sizes proportional to their sizes on the crystal itself, but making opposite faces on each pinacoid of equal width. The desired edges were obtained by drawing normals to the *a*- and *b*-axes.
6. Next the basal pinacoid (13) was drawn. Its size was made proportional to the size of the corresponding face on the crystal, and its center was made the center of the rhombus. It is bounded by the edges caused by pyramidal faces (9, 10, 11, 12) cutting it. The directions of these edges are normals to the lines joining face-poles 9–13, 10–13, 11–13, and 12–13, and are parallel to the prism outline. In a similar fashion the edges between the pyramidal faces were drawn, completing the orthographic projection. Figure 4*C* shows the way the completed orthographic projection should appear. Note that pyramid or dome faces that are steeply inclined (i.e., $\rho = 60\text{–}90°$) appear quite narrow in the orthographic projection.

PARALLEL PERSPECTIVE DRAWING (CLINOGRAPHIC PROJECTION)

1. This is made in the lower right-hand part of the large sheet of paper, using the orthographic drawing, the gnomonic projection, and the *guide line* and *angle point*.
2. To construct the guide line and angle point, proceed as follows: In the fundamental circle draw a diameter *AB* (Fig. 5) at right angles to the *b*-axis. From *B*, lay off a chord *BF* = one-third *OB*. Draw the diameter *FOE* and on *OE* lay off *OD* = one-sixth *OB* (the radius). Through *D* draw a line way across the large sheet of paper perpendicular to *FOE*. This line is called the *guide line*. Draw the radius *OJ* parallel to the guide line. The point at which *OF* is cut by a circle with center *D* and radius *DJ* is known as the *angle point*, and should be surrounded by a small square.
3. Now start the parallel perspective drawing. The position of the first crystal edge to be drawn is arbitrarily selected on the large sheet of paper at a convenient distance below the orthographic drawing. Be sure this first edge is one on the front of the crystal (an edge on the back of the crystal always has both the face-poles concerned above the guide line).
4. To find the direction of this first edge in the parallel perspective drawing, note where the line joining the two points in the gnomonic projection representing the two faces concerned cuts the guide line, and join this point to the angle point. The direction of the required edge will be perpendicular to the line so obtained.

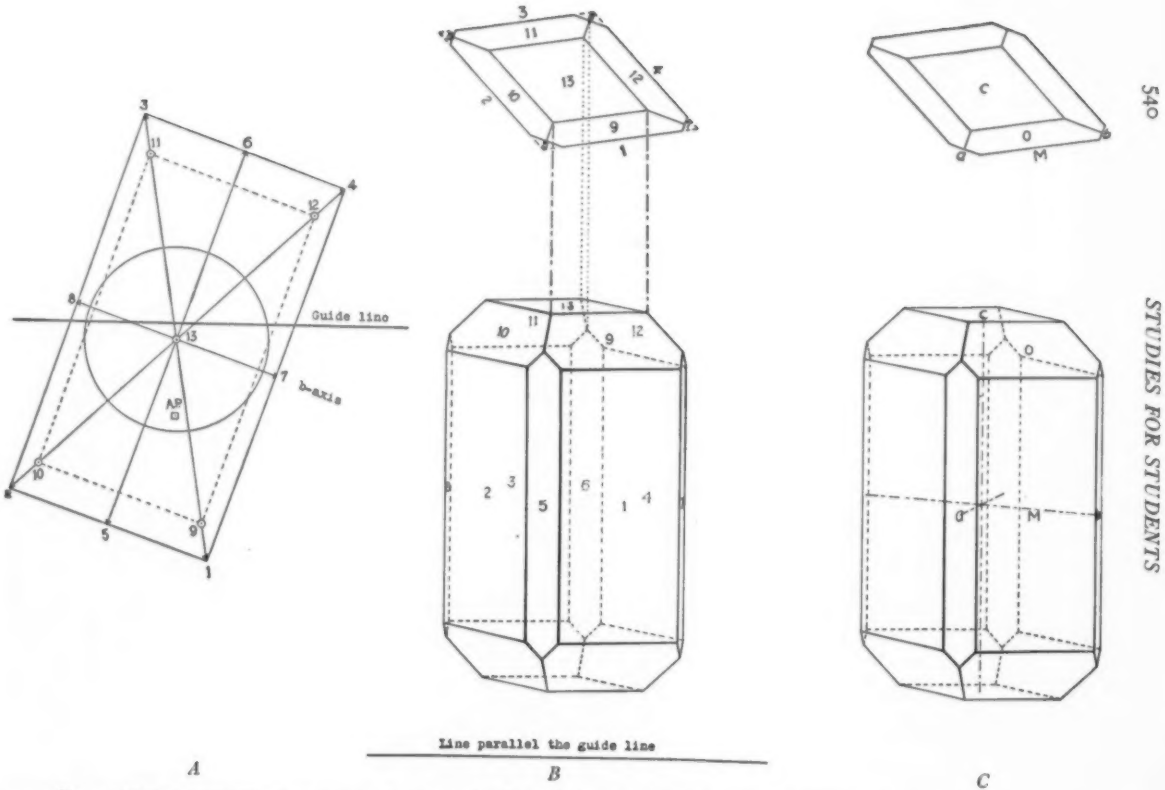

FIG. 4.—Various projections of topaz: *A*, gnomonic; *B*, preliminary orthographic and clinographic; *C*, completed orthographic and clinographic.

5. The length of this first edge is determined by dropping perpendiculars to the guide line which pass through the two ends of the corresponding edge in the orthographic projection.
6. Build on from this edge the other edges necessary to complete a face; then start on an adjacent face, and continue thus till the crystal is completed. Always determine the length of an edge before building on to it, else the crystal will not appear symmetrical.

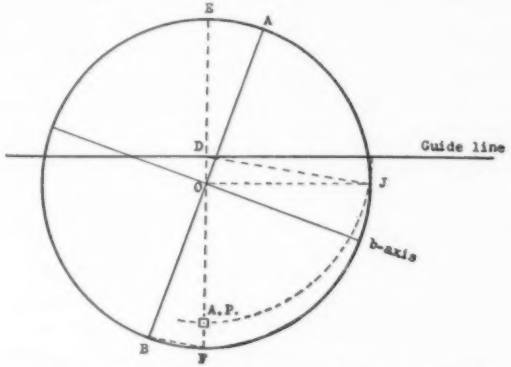

FIG. 5.—Method of construction of the guide line and angle point (A.P.)

7. In finding the direction of an edge between a prismatic face and a terminating face, pass a line (in the gnomonic projection) through the face-pole of the terminating face parallel to the direction of the arrow representing the prismatic face. This line cuts the guide line in the point needed. Proceed as in the latter part of paragraph 4 (above).
8. The direction of edges between prismatic faces in the parallel perspective projection is obtained by simply drawing normals to the guide line. In determining the length of the edges between the prismatic faces, preserve the dimensions of the crystal as was done in paragraph 5 under *Orthographic Drawing*.
9. Fig. 4*B* illustrates the method of drawing the clinographic projection. The edge between faces 9 and 13 was first drawn. Placing the straight edge on the angle point and the point on the guide line where a line through face-poles 9 and 13 cuts it, by means of a triangle a normal to the straight edge was made. This gave the direction of the edge between faces 9–13 in the clinographic projection. A line parallel to the guide line was drawn well below the orthographic projection. The straight edge was laid on this line and the triangle placed against the straight edge and normals to the guide line were dropped from the ends of the edge between faces 9–13 in the orthographic drawing, thus determining the ends of this edge in the

FIG. 4.—Various projections of topaz: *A*, gnomonic; *B*, preliminary orthographic and clinographic; *C*, completed orthographic and clinographic.

clinographic drawing. These normals to the guide line are shown by dot-and-dash lines in Fig. 4*B*.

10. Then the other edges bounding face 13 were drawn in the clinographic projection according to the foregoing rules. Next, face 9 was completed; and so on until all the faces in the parallel perspective drawing on the *front* of the crystal above the plane of the *a*- and *b*-axes were completed.
11. In drawing the edges on the back of the crystal above the plane of the *a*- and *b*-axes, the same rules are applied. Thus the edge between faces 11–12 was first drawn. Its direction was obtained from the gnomonic projection according to paragraph 4 above. Its length was determined by dropping normals (shown by dotted lines in Fig. 4*B*) to the guide line through the ends of the same edge in the orthographic projection. In similar fashion the remaining faces above the plane of the *a*- and *b*-axes were completed.
12. The edges between the faces on the lower half of the crystal may be drawn in with the face-poles already on the gnomonic projection proceeding according to the foregoing rules, except that the opposite face-poles are chosen. That is, in drawing the edge between the two pyramidal faces on the front of the lower part of the topaz crystal (Fig. 4*B*), the opposite face-poles (11 and 12) were used as directed in paragraph 4 above. The direction of the edge between face 5 and the lower right pyramidal face was obtained by passing a line through face-pole 11 parallel to arrow 5 and continuing according to the rules of paragraph 7 above. A simpler method (which holds for all crystals with a center of symmetry) is to prick through on another sheet of paper the corners already obtained for the upper part of the crystal, rotate this pricked paper 180° about the *a*-axis of the clinographic drawing of the crystal (considering the *a*-axis to be normal to the paper on which the crystal is drawn), and prick through the new points thus given on the original drawing, and join these points with lines parallel to corresponding lines on the upper half of the crystal.
13. If desired, the crystallographic axes may be added. The direction of the *c*-axis is given by a line normal to the guide line. The directions of the *a*- and *b*-axes can be obtained from the gnomonic projection according to the foregoing rules (paragraph 7) by taking the directions of the edges between the (010) and (001) and the (100) and (001) pinacoids, respectively. Of course, the axes should intersect at the center of the crystal.
14. The drawing is now ready to be inked. Edges between faces on the rear of the crystal should be shown by narrow dashed lines. The crystal axes are best shown by faint dot-and-dash lines. Edges between faces on the front of the crystal are shown by solid lines. Some crystallographers consider that the appearance of solidity is added to the projection if the edges which bound the faces on the front of the crystal at or near the center of the drawing are made with heavier lines, lighter lines being progressively used as the edges nearer the boundaries of the crystal are drawn. Fig. 4*C* shows the completed drawing.

REVIEWS

Climatic Changes. By ELLSWORTH HUNTINGTON and STEPHEN SARGENT VISHER. New Haven, Connecticut: Yale University Press, 1922. Pp. 329, figs. 13.

The forces which determine climate and the influence which it, in turn, exerts upon earth history and the evolution of life are inevitably of interest to students of casual relationships. The senior author of the book under discussion has published several previous studies to show climate as a very important factor in evolution. In the present book the authors explain climatic changes in the light of a new hypothesis which is more fully elaborated in *Earth and Sun*, a contemporary book by the senior author. The discussion of this hypothesis is followed by its application to climates of the past, both those of the remote history of the earth and those of historical times.

The authors briefly consider the main hypotheses which have been previously suggested to account for climatic change. Such previous theories are considered as only partially adequate to account for the recorded changes. For example (1) the action of carbon dioxide is thought to have been probably an important factor in producing only the longer oscillations of climate from one geological era to another; (2) the precession of the equinoxes must have had some climatic effect but is totally inadequate to account for all the known facts of glaciation; (3) the influence of the configuration of land areas, such as the extent of continents and the height of mountain ranges is conceded, but it is contended that they could not cause the more rapid fluctuations; (4) the influence of volcanic eruptions in lowering temperatures is noted but not found adequate to explain the systematic glacial variations; (5) the shifting of the relationship between the earth and its axis and (6) a permanent change in the amount of heat emitted by the sun are considered as being unsupported by geologic evidence.

In brief, it is considered that previous hypotheses have suggested only contributory causes for climatic variations.

The solar cyclonic hypothesis, however, whose elaboration is the chief contribution of this volume is not supposed to supersede the previous hypotheses, but is considered to explain some of the many conditions to which the others seem inadequate.

It is stated that the most important recent discovery of climatology is that variations in the weather depend on variations in the activity of

the sun's atmosphere. At the times when the sun emits the most energy, that is, when sunspots are the most numerous, the earth's storminess increases, since atmospheric pressure varies in harmony with the number of sunspots.

Many lines of evidence are presented to show the probability that historic climatic pulsations and glacial fluctuations are sunspot cycles on a smaller or larger scale. The celestial causes which might have occasioned particularly severe sunspot disturbances at long intervals in the past are outlined. Both shorter climatic variations and glacial periods are reviewed in the light of this hypothesis as well as the correspondence of the great periods of diastrophism with the great climatic cycles. And, finally, reference is made to the influence of climatic change upon life—the stimulus it gives toward new adaptations, to new lines of evolutionary progress.

It is a suggestive series of causes and effects which the book supports —the constantly changing relationship of the sun to its planets and to other celestial bodies initiates greater or less disturbances of the solar atmosphere; these, in turn, cause greater or less disturbances of the earth atmosphere, expressed in variations of temperature and atmospheric pressure which are at least contributing causes of minor climatic variations and of occasional greater fluctuations—the glacial periods. These climatic changes and the parallel disturbances of the earth's crust stimulate life to greater diversity and more rapid evolution.

The book is a distinct contribution to the study of the adjustment of force to force which constitutes terrestrial and organic evolution.

HERVEY W. SHIMER

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
March 25, 1924

The Geology of Corrour and the Moor of Rannoch. By HINXMAN, CARRUTHERS, MACGREGOR, CLOUGH, THOMAS, AND READ. Memoirs of the Geological Survey, Scotland. Volume LIV. Edinburgh, 1923. Pp. 96, figs. 6.

The country described is composed entirely of the crystalline metamorphic rocks of the Highlands and their associated igneous intrusions. The latter belong almost exclusively to the newer granite period of intrusion which was subsequent to the movements that produced the regional metamorphism and foliation of the altered sediments. The Moor of Rannoch granite is the most extensive formation and is considered to be probably of Lower Old Red Sandstone age.

A. H. B.